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Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines: Gaseous Emission Regulations for 1987 and Later Model Year Light-Duty Vehicles, Light-Duty Trucks, and Heavy-Duty Engines; Particulate Emission Regulations for 1987 and Later Model Year Heavy-Duty Diesel Engines

Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources

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16. ABSTRACT

This document summarizes the results of analyses conducted in support of proposed nitrogen oxide (NOx) emission standards for 1987 and later model year light duty trucks and the NOx and particulate standards for 1987 and later model year heavy-duty engines. (49 FR 40258, October 15, 1984).

The analyses include consideration of the costs and benefits of the proposed action as well as a comparison of the proposed action with alternative regulatory approaches. The report also includes the environmental impact analyses for NOx and diesel particulate standards.

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CHAPTER 1

INTRODUCTION

As required by Executive Order 12291 this document has been prepared to summarize the results of all analyses conducted in support of the proposed regulations. These analyses include a consideration of the costs and the benefits of the proposed action as well as a comparison of the proposed action with alternative regulatory approaches. The primary supporting analysis summarized in this document is the EPA Diesel Particulate Study, which examined the costs and benefits of a number of alternative diesel particulate regulatory approaches. Supporting analyses for the proposed NOx regulations are contained in this document. The background air quality data supporting the NOx environmental impact analysis may be found in the public docket. The NOx Environmental Impact Analysis contained in this document also serves as the NOx pollutant-specific study required by Section 202 (a)(3)(E) of the Clean Air Act.

I. Background of the Regulations

A. Clean Air Act Requirements

The Clean Air Act Amendments of 1977 created a statutory heavy-duty vehicle (HDV) class and established mandatory emissions reductions for that class. Under the language of the amendments, all vehicles over 6,000 lbs gross vehicle weight (GVW) were defined as "heavy duty" and were required to achieve a 75 percent reduction in NOx emissions from uncontrolled levels, effective with the 1985 model year.

The Act made no specific provisions for light-duty trucks (LDTs), which at that time only encompassed LDTs between 0 and 6,000 lbs GVW (light LDTs). These LDTs were regulated by EPA as a separate class under the general authority of the Clean Air Act. Beginning with the 1979 model year, EPA expanded its standards for the LDT class to 8,500 lbs GVW, thus encompassing those heavy LDTs (6,001 to 8,500 lbs GVW) which are subject to the heavy-duty vehicle provisions mentioned above.

The Act also authorizes the Administrator to temporarily establish revised standards for heavy-duty engines if the statutory standards cannot be achieved without increasing cost or decreasing fuel economy to an "excessive and unreasonable degree."[1] The heavy-duty engine NOx standards evaluated in this document are being proposed under these provisions of the Act.

The amendments of 1977 also require the "greatest degree of [particulate] emissions reduction achievable", given the availability of control technology and considering cost, leadtime and energy impacts.[2] These reductions were to begin during the 1981 model year. Although not specifically limited as to applicability in the language of the Amendments of 1977, it was recognized that the requirement was aimed at diesel vehicles/engines. The heavy-duty diesel engine (HDDE) particulate standards proposed in this NPRM are based on this authority.

B. Regulatory History

The first NOx standards antedated the Amendments of 1977. Prior to the 1975 model year, LDTs complied with the 3.0 g/mi NOx standard that had been established two years earlier for LDVs. With the splitting off of the LDT class for the 1975 model year, LDTs were required to meet a NOx standard of 3.1 g/mi, comparable in stringency to the LDV standard. Heavy-duty engines (HDEs) will have no separate NOx standard until the 1985 model year, however, there have been combined HC + NOx standards in place for HDEs since the 1974 model year. Table 1-1 shows Federal NOx and particulate standards for LDTs and HDEs from 1972 to 1986.

The current NOx standard for 1979 and later model year LDTs is 2.3 g/mi, comparable in stringency to the 2.0 g/mi standard established for LDVs of that year. Beginning in 1979, the LDT class was expanded to include vehicles between 6,001 and 8,500 lbs GVW. The current NOx standard for HDEs is 10.7 g/BHP-hr, established originally for the 1984 model year, but later made optional until the 1985 model year.

Turning now to more recent actions, an Advanced Notice of Proposed Rulemaking was promulgated for LDT and HDE NOx emissions in January of 1981 (46 FR 5838). Standards of 1.2 grams per mile for LDTs and 4.0 g/BHP-hr for HDEs were proposed effective for the 1985 and 1986 model years, respectively. These standards did not correspond to the statutory 75 percent reduction as noted above, but were proposed because they were comparable in stringency to the existing 1.0 g/mi LDV NOx standard in the case of LDTs and because they represented the lowest practicable standard given the available technology in the case of HDEs.

The first diesel particulate standards were established for LDVs and LDTs, effective beginning with the 1981 model year. A standard of 0.60 g/mi was established for both LDVs and LDTs, representing an achievable level for the (then) available technology. More stringent standards (at 0.26 for

Table 1-1

Exhaustive Emissions for LDTs and HDEs

(Federal Standards)

Model	LDT g/mi			HDE g/BHP-hr		
Year	NOx	Part.		NOx	HC+NOx	Part.
1972	--	--		--	--	--
1973	3.0	--		--	--	--
1974	3.0	--		--	16	--
1975-78	3.1	--		--	16	--
1979-81	2.3	--	A*	--	10**	--
			B*	--	5	--
1982	2.3	0.6	A*	--	10**	--
			B*	--	5	--
1983-84	2.3	0.6	A*	--	10**	--
			B*	--	5	--
			C*	10.7	--	--
1985-86	2.3	0.6		10.7	--	--

---

* A, B, and C designate regulatory options available for HDEs.

** If HC emissions do not exceed 1.5 g/BHP-hr.

LDTs, and 0.20 for LDVs) were also promulgated effective beginning with the 1985 model year, but these have been delayed and will now be effective for the 1987 model year (49 FR 3010, January 24, 1984).

For HDDEs, a Notice of Proposed Rulemaking was published in January, 1981 (46 FR 1910) which proposed a standard of 0.25 g/BHP-hr for 1986 and later model years. Because of the related technical issues that were raised during the comment periods for both the NOx ANPRM and the particulate NPRM and the interrelationship between NOx and particulate emissions, EPA has decided to issue a combined NPRM to address these issues and insure that manufacturers could direct their efforts at meeting a unified set of emission standards.

Also, this action represents the initial proposal of high-altitude particulate standards for diesel-powered LDTs and HDDEs.

II. Description of the Proposed Action

A. New Emissions Standards

This proposal contains new NOx standards for LDTs and HDEs and new particulate standards for light-duty diesel trucks (LDDTs) operated under high altitude conditions and for HDDEs operated under both high and low altitude conditions. The NOx standard for LDTs is proposed at 1.2 g/mi for LDTs up to 6,000 lbs GVW or 3,999 lbs equivalent test weight (ETW) to maintain comparability with the LDV standard of 1.0 g/mi that was established for the 1981 model year. The standard for LDTs over the above weight limits is 1.7 g/mi, primarily to facilitate compliance with the particulate standard for the heavier LDDTs. A staged NOx standard is proposed for HDEs to allow leadtime for further development of control technology. The NOx standard for 1987-89 model year HDEs is proposed at 6.0 g/BHP-hr, representing a level that is achievable given minimum leadtime for engines currently in production, with a more stringent standard of 4.0 g/BHP-hr to be effective for 1990 and later model year engines.

A phased particulate standard is also proposed for HDDEs. Model year 1987-89 HDDEs operated under low-altitude conditions would meet a standard of 0.60 g/BHP-hr. For 1990 and later model years, low-altitude urban bus engines will comply with a standard of 0.10 g/BHP-hr, while the remainder of the low-altitude HDDEs would meet a standard of 0.25 g/BHP-hr. Both of these proposed 1990 standards will likely require the use of trap oxidizers on a majority of applications. These standards represent the approximate lower limit of feasibility given the above-mentioned NOx standard. HDDEs operated under high-altitude conditions, including urban bus engines, would comply with standards of 0.72 g/BHP-hr beginning in the 1987 model year and 0.30 g/BHP-hr (0.12 g/BHP-hr for urban buses) effective for 1990 and later model years. Finally, a particulate standard of 0.26 g/mi is proposed for LDTs operated under high-altitude conditions. These proposed standards are summarized in Table 1-2.

B. Extension of Particulate Averaging to 1990 and Later Model Year HDDES

Diesel particulate averaging has been included for 1990 and later HDDEs as a means of reducing the cost of compliance with the 0.25 g/BHP-hr standard. Under existing regulations, manufacturers of 1987 and later model year light-duty diesel vehicles (LDDVs) and light-duty diesel trucks (LDDTs) will have the option of averaging particulate emissions from their products. This provision is designed to allow some vehicles to exceed the standard as long as the manufacturer's corporate average light-duty diesel particulate emission level is below the applicable standard, or below a production-weighted average standard if the manufacturer's product line includes both LDDVs and LDDTs. With this rulemaking, particulate averaging will also be afforded to manufacturers of 1990 and later model year HDDEs. However, they would not be allowed to average HDDEs with LDDTs or LDDVs if the manufacturer's product line also includes these vehicle types. Similarly, averaging high altitude or California engines with engines intended for sale in low altitude non-California areas will not be permitted, although averaging within each of these areas is allowed. Urban buses will be excluded from the averaging program to insure the maximum reduction in urban particulate emissions. Because HDDE standards are expressed in mass per unit of work (g/BHP-hr) rather than mass per unit of distance travelled (g/mi) and because HDDEs are divided into subclasses with widely varying useful life periods, averaging will be limited to within each of the existing subclasses (light-, medium-, and heavy-heavy duty) and the calculation of average particulate emissions must include weighting factors for brake horsepower as well as for production volume.

C. New Allowable Maintenance Regulations

The allowable maintenance provisions (§86.087-25) have been simplified and streamlined to a large extent. The concept of emission- and non-emission-related maintenance has been extended from LDTs and HDEs to encompass LDVs as well. Maintenance intervals have been changed, as outlined in the preamble, and manufacturers will be required to demonstrate the likelihood of in-use performance for certain critical emission-related maintenance.

Table 1-2

Proposed NOx and Particulate Standards for LDTs and HDES

Effective Model Year	Vehicle Class	Applicable Standards NOx	 Particulate*
Low Altitude:			
1987	LDT1**	1.2 g/mi	***
	LDT2**	1.7 g/mi	***
	HDE	6.0 g/BHP-hr	0.6 g/BHP-hr
1990	LDT1**	1.2 g/mi	***
	LDT2**	1.7 g/mi	***
	HDE Urban Bus	4.0 g/BHP-hr	0.1 g/BHP-hr
	All Other	4.0 g/BHP-hr	0.25 g/BHP-hr
High Altitude:			
1987	LDT1**	1.2 g/mi	0.26 g/mi
	LDT2**	1.7 g/mi	0.26 g/mi
	HDE	6.0 g/BHP-hr	0.72 g/BHP-hr
1990	LDT1**	1.2 g/mi	0.26 g/mi
	LDT2**	1.7 g/mi	0.26 g/mi
	HDE	4.0 g/BHP-hr	0.30 g/BHP-hr

---

* Diesel-powered vehicles/engines only

** LDT1 - vehicles up to 6,000 lbs GVW or 3,999 lbs ETW.
LDT2 - vehicles 6,001-8,500 lbs GVW or 4,000 lbs or greater ETW.

*** 1987 and later model year LDTs are currently required to comply with a standard of 0.26 g/mi. No new standards are being proposed.

D. Miscellaneous Standards and Test Procedure Revisions

The current idle CO standard for gasoline-powered LDTs has been extended to cover vehicles intended for sale in designated high altitude areas. This extension will allow the development of more representative cutpoints for inspection/maintenance programs in high altitude areas and thus facilitate the detection of failed catalytic converters.

Since there is currently no particulate standard (and consequently no particulate test procedures) for HDDEs, it was necessary to incorporate suitable test procedures into Subpart N. EPA is also proposing a humidity correction factor to be applied in the calculation of NOx emission test results for HDEs, and a correction factor to be used when HDGE NOx emissions data are obtained through continuous sampling, as opposed to the more common bag sampling, techniques.

III. Organization of the Regulatory Impact Analysis

The remaining six chapters of this Regulatory Impact Analysis will be divided as follows: Chapter Two will deal with the technological feasibility of compliance with the proposed standards. Chapter Three presents an analysis of the economic impact of the proposed regulations. Chapter Four analyzes the environmental effects of the proposed NOx standards while Chapter Five performs the same function for the proposed particulate standards. An analysis of the cost effectiveness of the proposed regulations is presented in Chapter Six, and the regulatory alternatives considered are discussed in Chapter Seven.

References

1. The Clean Air Act As Amended August 1977, Serial No. 95-11, Section 202(a)(3)(B)&(C).

2. IBID; Section 202 (a)(3)(iii); p. 102.

Chapter 2

Technological Feasibility

I. Introduction

This chapter analyzes the technical feasibility of nitrogen oxide (NOx) emission standards for 1987 and later model year light-duty trucks (LDTs), and the feasibility of NOx and particulate emission standards for 1987 and later model year heavy-duty engines (HDEs). Current emission levels are discussed, as are the emission reductions which are judged to be attainable by 1987 and by 1990. Specific technologies required to achieve these emission reductions are identified. Other factors considered in this analysis include the fuel economy and performance implications of increased emission control. After due consideration is given to other regulatory requirements (i.e., compliance with standards over the full useful life and assembly-line testing), 1987 LDT, and 1987 and 1990 model year HDE emission standards are recommended.

The analytical methodologies used in this analysis will be explained as presented.

II. Light-Duty Trucks (LDTs)

A. Introduction

This analysis will address the feasibility of two LDT NOx standards in 1987: 1) 1.2 g/mi for all LDTs, 2) 1.2 g/mi for lighter LDTs and 1.7 g/mi for heavier LDTs. Note that 1987 is also the model year in which more stringent particulate standards (.26 g/mi) go into effect for light-duty diesel trucks (LDDTs). The feasibility of this particulate standard, however, has already been addressed in the rulemaking.[1,2]* This analysis will consider the particulate standard as given, and will only address the feasibility of additional NOx control. However, the effect of NOx control on the type of technology needed to meet the particulate standard will be addressed.

First of all, the feasibility of a 1.2 g/mi NOx standard for 1987 light-duty gasoline-fueled trucks (LDGTs) will be addressed. The analysis will consider the inherent similarity between LDGTs and light-duty gasoline-fueled vehicles (LDGVs) in assessing the feasibility of the 1.2 g/mi standard. Available emission certification data will be extensively used, and fuel economy effects of the standard will be estimated.

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* In determining the 1987 LDDT particulate standard of 0.26 g/mi to be feasible, EPA's analysis assumed a simultaneous NOx standard of 1.2 g/mi.[2]

Secondly, this analysis will examine the feasibility of the 1.2 g/mi NOx standard for 1987 LDDTs. Again, a review will be made of available emission certification data. A large part of the discussion will address the specific compliance capabilities of the heaviest trucks.

Thirdly, the feasibility of a 1.7 g/mi NOx standard for the heavier LDTs (i.e., those LDTs with an equivalent test weight (ETW) above 4,000 lbs or a gross vehicle weight above 6,000 lbs) will be discussed, along with a detailed presentation of its fuel economy implications, as well as its effect on diesel particulate control technology.

B. Light-Duty Gasoline-Fueled Trucks (LDGTs)

1. Low Mileage Target Derivation

Typically, the first step in determining the feasibility of a given emission standard is to determine the low mileage emission target levels. (Manufacturers must calibrate their emission control systems on certification and production vehicles somewhat below the actual emission standard to account for in-use emissions deterioration and production line emissions variability. This is done to assure that the average production vehicle will comply with the applicable emission standard over its entire useful life.) There are three factors which must be considered in developing the target emission level: the emission standard itself expressed as the maximum pass level (MPL), the Selective Enforcement Audit (SEA) adjustment factor (AQL) necessary to account for production-line variability and to provide the manufacturer confidence that no more than 40 percent of its vehicles will fail a formal SEA, and the full-life multiplicative deterioration factor (DF). The design target emission level (TL) is, therefore, calculated as follows for LDTs:

$$TL = \frac{1}{AQL} \times \frac{1}{DF} \quad (MPL)$$

Because, however, different emission-control technologies can exhibit different rates of deterioration, this LDGT discussion begins with a brief description of likely 1987 LDGT emission-control technologies.

LDGT emission-control technologies are identical in concept and design to the systems used on LDGVs. Indeed, the best predictor of likely 1987 LDGT emission-control strategies are current LDGVs. Both vehicle classes are certified on the same chassis dynamometer test procedure. Both vehicle classes share the same technologies, and in many cases share the same engines and/or components. Both vehicle classes are subject to Corporate Average Fuel Economy (CAFE) standards. Current LDGVs are required to meet a NOx standard of 1.0 g/mi; the 1987 LDT 1.2 g/mi standard was specifically derived to be comparable in stringency* to the 1.0 g/mi LDV standard.[4] In summary, the emission control technologies present in current LDGVs will most likely be adopted for 1987 LDGTs. As will be noted below, 42 percent of current LDGTs are already equipped with advanced NOx control technology found on LDGVs.

The types of catalyst emission control systems present in current LDVs are shown in Table 2-1. With respect to NOx control, and especially with respect to NOx deterioration, there are only two relevant systems: those systems which use three-way reduction catalyst technology and those which do not. (As shown in Tables 2-2 and 2-3, 38 of 40 1984 LDGT engine families are equipped with EGR in both three-way and non-three-way catalyst systems; as EGR is used to the same extent in both, it need not be considered when discussing differential deterioration rates between the catalyst systems.) Deterioration for both types of catalyst systems need to be characterized since both systems are applicable to LDGTs, although three-way systems appear to be overwhelmingly preferred in LDV applications (see Table 2-1).

Average NOx deterioration factors (DFs) for each catalyst system can now be derived from existing emission certification data. Tables 2-2 and 2-3 present 1984 certification data for LDGT engine families equipped with reduction (three-way) catalysts and non-reduction catalyst technology, respectively. Note that the multiplicative deterioration factors presented in both tables only address deterioration over 50,000 miles (half life). To derive a "typical" full-life NOx DF for both reduction catalyst and non-reduction catalyst technology, the average half-life DF from Tables 2-2 and 2-3 must be adjusted. Using the appropriate methodology,** average multiplicative full-life NOx DFs of 1.286 for three-way and 1.070 for non-threeway systems are derived. A larger DF for catalyst-based NOx control (three-way technology) is expected because of the inherently greater deterioration typically observed in catalyst-based emission control systems.

---

* A significant difference between the classes with respect to emissions is that LDTs, on average, are heavier than LDVs. Since more energy (i.e., more fuel) is required to push a heavier vehicle over the road, more exhaust products are formed per mile of travel. Therefore, for a given LDV standard, a slightly higher numerical standard for LDTs provides equivalently stringent control.

** Assuming linear deterioration over the full useful life, the full-life multiplicative DF = 1 + 2.4 (half-life DF - 1), where 2.4 = 120,000 miles (full-life distance)/50,000 miles (half-life distance).

Table 2-1

Market Share* by ECS for Light-Duty Vehicles

Emission Control System (ECS)	1981	1982	1983
OLC + O[illegible]	13.80%	11.55%	8.67%
OLC + 3W	2.39%	2.11%	0.32%
OLC + 3W + OC	11.84%	16.63%	10.73%
FBC + 3W	21.33%	12.82%	3.50%
FBC + 3W + OC	35.81%	30.29%	36.85%
OLFI + OC	0.02%	0.00%	0.00%
OLFI + 3W + OC	0.01%	0.02%	0.02%
FBFI + 3W	6.12%	16.46%	22.10%
FBFI + 3W + OC	2.68%	2.53%	9.36%
Diesel	6.02%	7.58%	8.45%
Total 3W:	80.18%	80.86%	82.88%
Total Non-3W:	13.82%	11.55%	8.67%
Total Open Loop:	28.06%	30.31%	19.74%
Total Closed Loop:	65.94%	62.10%	71.81%
Total Non-Diesel:	94.00%	92.41%	91.55%

---

* The market share was calculated using the data base from Reference 3.

Abbreviations

OLC = Open-loop carburetor.
OLFI = Open-loop fuel injection (FI).
FTB = Feedback throttle body.
OC = Oxidation catalyst.
3W + OC = Three-way-plus-oxidation catalyst.
FBC = Feedback carburetor.
3W = Three-way catalyst.
FBFI = Feedback FI.

Table 2-2

1984 Certification Data for LDGTs
Equipped With Three-Way-Catalyst Technology

Manufacturer	Engine Family	Emission Control Technology*	Cert. NOx DF	Low-Mileage NOx Level
American Motors	EAM150T1HEA5	EGR/PLS/3CL	1.375	0.35-1.1
	EAM258T2HEAX	EGR/PLS/3CL	1.045	0.75-1.8
	EAM360T2HLEX	EGR/PMP/3WY	1.100	1.1-1.4
Dutton	EDN6.0T4HRAX	EGR/PMP/OXD/3CL	1.100	1.4
Ford Motor Company	EFM2.3T1HKG9	EGR/PMP/OXD/3CL	1.000	0.77-2.0
	EFM2.8T2HCG1	EGR/PMP/OXD/3CL	1.464	0.50
	EFM4.9T1HGG5	EGR/PMP/OXD/3CL	1.000	0.45-0.98
	EFM5.0T2GAF2	EGR/PMP/OXD/3WY	1.060	1.3-1.5
	EFM5.8T2HGG0	EGR/PMP/OXD/3CL	1.000	0.57-1.9
	EFM5.8T24GAF3	EGR/PMP/OXD/3WY	1.060	1.7-1.8
Fuji	EFJ1.8T5FFH1	EGR/3CL	1.100	0.69
General Motors	E1G1.9T2TBA8	EGR/PMP/3CL	1.316	0.35
	E1G2.8T2TRA2	EGR/PMP/3CL	0.892	0.71
	E1G5.7T4TYA4	EGR/PMP/3CL	0.996	0.48
Mitsubishi	EMT2.6T2FCJ3	EGR/PLS/3CL/OTR	1.039	0.73-0.78
Suzuki	ESK1.0T1FSF6	3CL	1.085	1.4
Toyota	ETY2.0T5FBB2	EGR/3CL/OTR	1.308	0.18-0.20
	ETY2.4T2FBBO	EGR/PMP/3WY/OTR	1.000	0.39-0.56
	ETY2.4T5FBB4	EGR/3CL/OTR	1.293	0.12-0.26
Volkswagon	EVW1.9T5CVA2	3CL	1.000	0.33
		Average:	1.119	

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* EGR = Exhaust gas recirculation
3CL = 3-way catalyst, closed loop fuel control
PMP = Air pump
OTR = Other
PLS = Pulse air injection
3WY = 3-way catalyst, open-loop fuel control
OXD = Oxidation catalyst

Table 2-3

1984 Certification Data for LDGTs
Equipped Without Three-Way Catalyst Technology

Manufacturer	Engine Family	Emission Control Technology	Cert. NOx DF	Low-Mileage NOx Level
American Motors	EAM2.8T2AXF2	EGR/PMP/OXD	1.079	1.5-1.7
Chrysler	ECR2.2T2AAB5	EGR/PMP/OXD	1.000	1.7-2.0
	ECR2.6T2AAC8	EGR/PLS/OXD	1.006	2.0-2.3
	ECR3.7T1BBBO	EGR/PMP/OXD	1.000	1.5-1.8
	ECR5.2T2BBF5	EGR/PMP/OXD	1.000	1.7-1.8
	ECR5.2T4BAFO	EGR/PMP/OXD	1.000	2.1-2.2
	ECR5.9T4BAF9	EGR/PMP/OXD	1.000	1.3-1.5
Fuji	EFJ1.8T2AFD3	EGR/PLS/OXD	1.000	1.2-1.3
General Motors	E1G1.9T2HFC9	EGR/PMP/OXD	1.000	1.7-2.0
	E1G2.0T2HJCX	EGR/PMP/OXD	1.000	1.8-2.1
	E1G2.8T2HTC7	EGR/PMP/OXD	1.079	1.7-1.9
	E1G4.1T2HHD3	EGR/PMP/OXD	1.090	1.6-1.7
	E1G5.7T4HHCX	EGR/PMP/OXD	1.000	1.6-2.2
Isuzu	ESZ119T2AAG1	EGR/PMP/OXD	1.000	1.6-1.8
Mitsubishi	EMT2.0T2AFD5	EGR/PLS/OXD	1.000	1.4-1.7
	EMT2.0T2BCAX	EGR/PLS/OXD	1.102	0.67-0.73
	EMT2.6T2AFD8	EGR/PLD/OXD/OTR	1.158	1.2-1.9
	EMT2.6T2BCA2	EGR/PLS/OXD/OTR	1.046	0.46-0.88
	EMT2.6T2BFJ8	EGR/PLS/OXD/OTR	1.046	1.6-1.7
Nissan	ENS2.4T2AAF0	EGR/PLS/OXD	1.095	1.3-1.5
Toyo Kogyo	ETK2.0T2AFL7	EGR/PLS/OXD	1.052	1.6-1.8
Toyota	ETY2.4T2AFFO	EGR/PLS/OXD/OTR	1.000	1.2-1.8
	ETY4.2T2AFF4	EGR/PMP/OXD/OTR	1.000	0.99
		Average:	1.029	

The next step in low-mileage target determination is the derivation of the production variability (AQL) factors for NOx emissions. An elaborate statistical analysis of LDT production variability will not be performed here, primarily because such precision is not important to this particular discussion,* and also because sufficently accurate estimates have already been derived.[5] For this analysis, a range of likely AOL factors will be used for all LDGTs. A typical range of AQL factors for a variety of engines and vehicles is 1.1 to 1.3. (Numbers in this range have been used in previous analyses[5,6], and are used elsewhere in this analysis.) These values represent conservative maximum and minimum factors likely to be observed in production.

Using the full-life DFs derived above, the full range of likely AQL factors and a MPL of 1.2499 g/mi, LMTs of 0.8-0.9 g/mi for three-way systems and 0.9-1.1 g/mi for non-three-way systems are calculated. The difference in target levels entirely reflects the difference in NOx deterioration rates between the three-way and non-three-way systems.

2. Current Technology LDGTs

Tables 2-2 and 2-3 also present a summary of available 1984 model year Federal certification test data for LDGTs.

Table 2-2 presents engine families equipped with three-way technology which, according to manufacturers' confidential sales projections, will account for about 42 percent of Federal 1984 LDGT sales. Two significant observations can be made from this table. First of all, 15 of the 20 families have one or all vehicle configurations below the 0.8-0.9 g/mi target range (i.e., less than 0.8 g/mi). In short, these families have already demonstrated the ability to comply with the 1987 1.2 g/mi standard. (These 15 families represent about 30 percent of total projected 1984 LDGT sales as well as a wide range of LDGT sizes (2875-4925 lbs ETW).) The second major observation involves the five families above the target level. Three of these families are equipped with open-loop fuel control, (i.e., there is no exhaust oxygen sensor to provide feedback to the microprocessor-based feedback fuel control system. Since precise fuel metering is essential to the efficient operation of a three-way catalyst, the adoption of closed-loop fuel control for these families would almost certainly allow some degree of reduction in NOx emissions. (These three families represent about 11 percent of total projected 1984 LDGT sales.) The emissions performance of the engine families presented in Table 2-2 demonstrates the overall feasibility of the 1.2 standard.

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* It will be readily apparent from this analysis that the NOx reducing ability of available LDGT technology is sufficiently great that any uncertainty induced by an imprecise AQL factor is immaterial to a conclusion of feasibility.

Table 2-3 presents the remaining 1984 Federal engine families certified for sale without three-way technology. These families represent almost 58 percent of projected 1984 LDGT sales. Three notable points can be made from this data. First, the range of average NOx emissions for these families is 1.4 to 1.7 g/mi, well below the 2.3 standard of course, but well in excess of either the .8 - .9 or .9 - 1.1 target ranges for the 1.2 standard. Obviously, recalibrations or additions of hardware will need to be made in the majority of these families to meet a 1987 1.2 g/mi standard. Second, three of the families (representing about .2 percent of 1984 sales) exhibit NOx emissions below 1.0 g/mi, and can be judged to already exhibit the ability to comply with a 1.2 standard with very little change. Finally, an additional five families (representing about 10 percent of 1984 sales) exhibit NOx emissions at or below 1.3 g/mi in at least one configuration, and at least hint at the possibility that some families through minor changes (i.e., EGR and timing recalibrations) could comply with a 1.2 g/mi NOx standard using the existing oxidation catalyst system.

These observations from Tables 2-2 and 2-3, along with other information, represent the basis for the following analysis of the feasibility of a 1.2 g/mi NOx standard for 1987 and later model year LDGTs.

3. Implications of a 1.2 g/mi 1987 LDGT NOx Standard

The data presented in Table 2-2 and discussed above, along with the demonstrated ability of substantially identical LDGVs to comply with a NOx standard of comparable stringency, establish for all practical intents and purposes the inherent feasibility of a 1.2 g/mi NOx standard for all 1987 LDGTS, if closed-loop three-way technology is assumed. Indeed, the 1984 three-way fleet exhibits NOx emissions 40 - 50 percent lower, on average, than the non-three-way fleet; many of these vehicles are already complying with a 1.2 g/mi standard. This conclusion of feasibility has not been disputed by any manufacturer, and warrants no further discussion.

The remainder of the LDGT analysis will concern itself with the possibility that some LDGT families may not need to adopt complete closed-loop three-way systems. An attempt will be made to predict the likely 1987 fleetwide emission control system product mix under a 1.2 NOx standard, taking into account product performance and fuel economy tradeoffs. Finally, a projection of the fleetwide fuel economy impact of the 1.2 standard will be made.

Table 2-4 presents our predictions for market shares of emission control technologies for 1987 LDGTs meeting a 1.2 NOx standard, along with the assumptions made in generating these predictions. As indicated by the results, it is reasonably certain that 90 percent or more 1987 LDGTs will be equipped with closed-loop three-way catalyst technology. The remaining vehicles may or may not, primarily depending upon the individual product choices of the individual manufacturers.

To evaluate the fuel economy implications of a 1.2 standard with the projected market mix of Table 2-4, a more detailed description of current LDGTs is necessary than the one presented above (which concerned itself only with emission control systems).* Tables 2-5 and 2-6 present more detailed vehicle data for the engine families presented earlier in Tables 2-2 and 2-3; Table 2-7 presents average values for the important parameters listed in Tables 2-5 and 2-6.

The current emission control product mix itself is an important clue to the relative fuel economies of the two emission control technologies. For any given gasoline engine, there is a point beyond which increasing EGR or recalibrating ignition timing for lower NOx will begin to impair fuel economy and performance (see Figures 2-1 and 2-2). Since EGR and timing recalibrations are less expensive than three-way systems, and assuming the rational allocation of funds by the manufacturers, the existence of three-way systems on current vehicles strongly suggests that a point of unacceptable fuel economy or performance tradeoffs has already been reached at a 2.3 g/mi NOx level for 42 percent of the vehicles.** Therefore, for any level of standard below 2.3, one would expect three-way

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* The baseline for this comparison is the 2.3 g/mi standard.

** There are several conceivable determinants of emission control system configuration. Factors such as cost, vehicle weight, fuel economy, vehicle application, product-line standardization (including standardization between LDGVs and LDGTs), the ratio of engine displacement to vehicle weight, individual engine characteristics, subjective driveability assessments, etc. are taken into account. Manufacturers have some flexibility, even with emission constraints, in configuring a total vehicle package.

Table 2-4

Present and Projected Market Shares of Emission Control Technology

Technology	1984 LDGTs (NOx=2.3 g/mi)[1]	1983 LDGVs (NOx=1.0 g/mi)[2]	1987 LDGTs (NOx=1.2 g/mi)
Non-Three-Way (open-loop)	58%	10%	0.2 - 5%[3]
Three-Way (open-loop)	11%	12%	0.4 - 3.7%[4]
Three-Way (closed-loop)	31%	78%	91 - 99%[5]

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[1] Based upon Tables 2-2 and 2-3, and manufacturers' confidential projected 1984 LDGT sales estimates.

[2] From Table 2-1, these percentages have been changed to exclude diesels from the total.

[3] Lower limit is based upon the three open-loop oxidation catalyst systems already emitting below 1.0 g/mi. NOx. (See Table 2-3.) Upper limit is based upon the additional five open-loop, oxidation catalyst systems with current emission levels below 1.3 g/mi NOx, and the assumption that 50 percent of these vehicles can meet the 1.2 standard with increased EGR and recalibrations instead of with three-way technology (see Table 2-3).

[4] The minimum projection assumes that all current three-way, open-loop Ford families adopt closed-loop technology for fuel economy reasons, while the one three-way open-loop Toyota family remains open loop. Upper limit is based upon the assumption that only manufacturers which today use open-loop three-way systems in LDGVs would consider their use for future LDGTs. AMC, Toyo Kogyo, and Toyota are the only LDGT manufacturers in this category with current open-loop-oxidation catalyst LDGTs. However, since Toyo Kogyo has chosen to go completely closed loop in a 1983 LDGV engine of identical displacement as their currently open-loop oxidation catalyst LDGT family, we project that it will also go closed loop in the 1987 LDGT.

[5] Remainder.

Table 2-5

Vehicle Data for 1984 Federal LDGTs Equipped With Three-Way Catalyst Technology (see Table 2-2)

Manufacturer	Engine Family	Eng. Disp. (liters)	Mean N/V ratio	Mean Vehicle Road Load (hp)	Mean Vehicle Equivalent Test Weight (lbs)	Mean City mpg
American Motors	EAM150T1HEA5	2.5	44.3	13.3	3,400	20.3
	EAM258T2HEAX	4.2	34.6	14.1	4,000	18.0
	EAM360T2HLEX	5.9	38.4	16.4	4,750	11.4
Dutton	EDN6.0T4HRAX	6.0	38.2	19.0	6,000	11.5
Ford Motor Company	EFM2.3T1HKG9	2.3	47.8	10.9	3,200	21.7
	EFM2.8T2HCG1	2.8	45.0	13.0	3,375	18.4
	EFM4.9T1HGG5	4.9	29.8	15.6	4,575	15.8
	EFM5.0T2GAF2	5.0	41.5	20.0	5,125	12.8
	EFM5.8T2HGG0	5.8	38.9	17.0	4,925	12.5
	EFM5.8T24GAF3	5.8	42.5	17.4	4,875	11.6
Fuji	EFJ1.8T5FFH1	1.8	47.0	9.6	2,875	24.1
General Motors	E1G1.9T2TBA8	1.9	47.0	10.4	3,000	24.2
	E1G2.8T2TRA2	2.8	38.2	12.0	3,500	19.5
	E1G5.7T4TYA4	5.7	25.4	16.6	4,750	14.6
Mitsubishi	EMT2.6T2FCJ3	2.6	51.6	15.8	3,550	19.0
Suzuki	ESK1.0T1FSF6	1.0	84.1	13.0	2,250	28.1
Toyota	ETY2.0T5FBB2	2.0	41.7	14.9	3,375	24.6
	ETY2.4T2EBB0	2.4	40.7	14.9	3,300	20.8
	ETY2.4T5FBB4	2.4	39.0	12.7	3,000	24.5
Volkswagen	EVW1.9T5CVA2	1.9	55.9	17.6	4,000	16.8

Table 2-6

Vehicle Data for 1984 Federal LDGTs Equipped With Oxidation Catalyst Technology (see Table 2-3)

Manufacturer	Engine Family	Eng. Disp. (liters)	Mean N/V ratio	Mean Vehicle Road Load (hp)	Mean Vehicle Equivalent Test Weight (lbs)	Mean City mpg
American Motors	EAM2.8T2AXE2	2.8	41.6	14.0	3,500	18.7
Chrysler	ECR2.2T2AAB5	2.2	39.6	10.1	3,500	22.7
	ECR2.6T2AAC8	2.6	44.2	10.1	3,450	21.2
	ECR3.7T1BBB0	3.7	42.6	16.8	4,500	15.5
	ECR5.2T2BBF5	5.2	39.2	18.1	5,000	12.5
	ECR5.2T4BAF0	5.2	39.7	18.4	4,750	12.2
	ECR5.9T4BAF9	5.9	40.0	19.7	5,375	10.2
Fuji	EFJ1.8T2AFD3	1.8	48.5	9.6	2,800	24.8
General Motors	E1G1.9T2HEC9	1.9	42.8	10.4	2,925	26.4
	E1G2.0T2HJCX	2.0	49.9	12.0	3,700	19.7
	E1G2.8T2HTC7	2.8	42.8	13.5	3,875	15.8
	E1G4.1T2HHD3	4.1	36.6	17.0	4,750	15.0
	E1G5.7T4HHCX	5.7	30.3	16.7	4,725	14.8
Isuzu	ESZ119T2AAG1	2.0	31.0	13.0	3,250	22.2
Mitsubishi	EMT2.0T2AFD5	2.0	48.7	11.9	2,950	25.3
	EMT2.0T2BCAX	2.0	48.7	11.9	2,950	23.9
	EMT2.6T2AFD8	2.6	[illegible].3	12.4	3,200	22.2
	EMT2.6T2BCA2	2.6	46.3	12.4	3,200	21.4
	EMT2.6T2BFJ8	2.6	27.2	15.9	3,625	19.6
Nissan	ENS2.4T2AAF0	2.4	48.1	13.0	3,300	21.4
Toyo Kogyo	ETK2.0T2AFL7	2.0	44.5	11.4	3,000	26.1
Toyota	ETY2.4T2AFF0	2.4	39.2	14.8	3,200	22.0
	ETY4.2T2AFF4	4.2	45.2	17.0	4,500	11.8

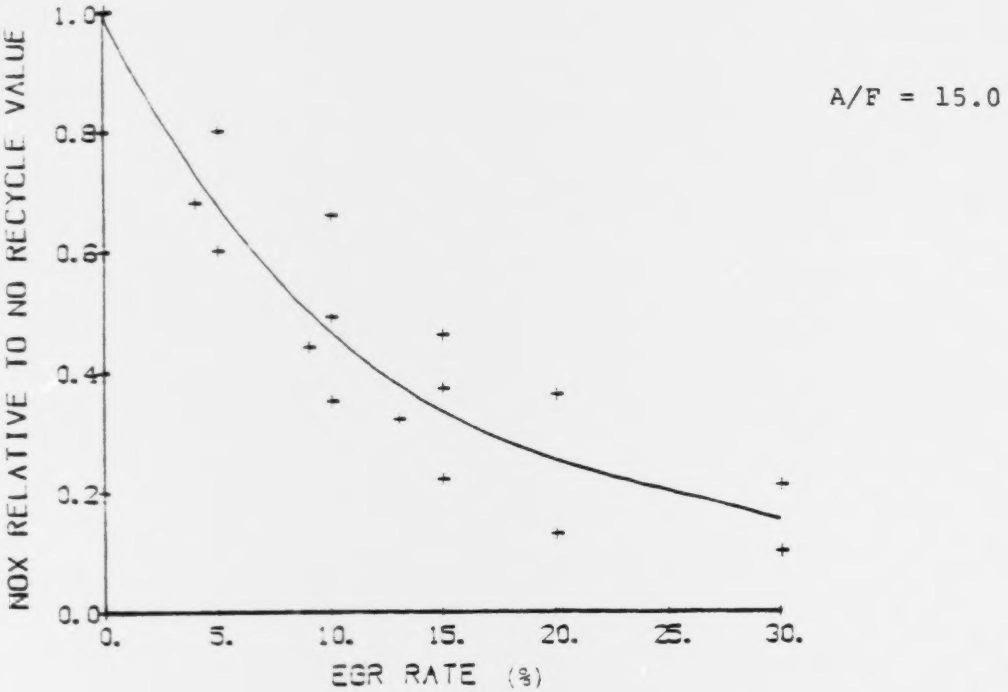
Table 2-7

Summary Values From Tables 2-5 and 2-6
For Federal 1984 LDGTs

	EPA City mpg	Engine Disp. (liters)	Equivalent Test Weight (lbs)	Road Load hp	N/V Ratio
Three-Way Family Average	18.5	3.49	3,891	14.7	43.6
Non-Three-Way Family Average	19.4	3.07	3,740	13.9	41.9

Figure 2-1

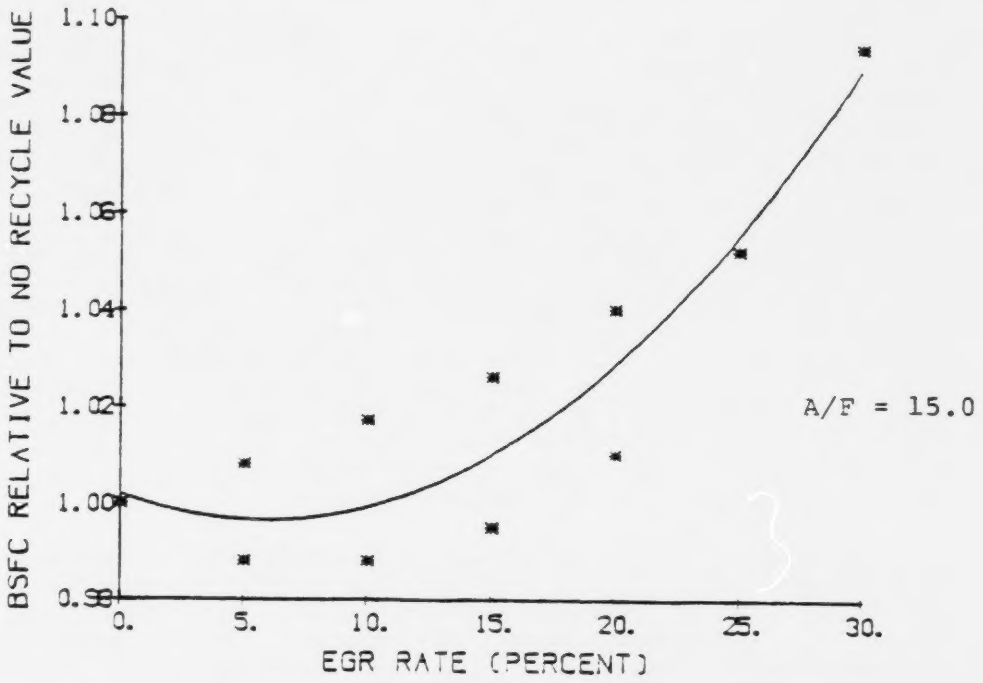
EGR Effect on Gasoline Engine NOx



NOTE: This graph was assembled from data presented in several references,[9,10,11,12] and is a representative depiction of the NOx reduction capabilities of EGR. For example, if a current LDGT is assumed to be calibrated at an average EGR rate of 10 percent, with emission rates from 1.4 to 1.7 g/mi NOx (see Table 2-3), then to reduce NOx emissions through EGR by 50 percent (i.e., to levels of 0.7 to 0.9 g/mi), NOx will need to be reduced from .5 to .25 on the relative scale above, requiring an increase in EGR from 10 percent to 20-25 percent.

Figure 2-2

The Effect of EGR Rate on BSFC
in a Conventional Gasoline Engine



NOTE: This graph was assembled from data presented in several references.[9,10,11,12] Continuing the example begun in Figure 2-1, engines which have EGR rates increased from 10 percent to 20 - 25 percent to lower g/mi NOx by 50 percent will experience an increase in BSFC, and presumably a decrease in mpg, of three to seven percent (from .980 to 1.01 - 1.05 relative BSFC). Vehicle driveability and performance implications of such EGR rates are unknown, being by necessity determined by subjective driver evaluations. However, at least one reference[10] reports significant engine misfire beginning at EGR rates between 25 and 30 percent, corresponding to an approximate fuel economy penalty of about 10 percent (relative to a 10 percent EGR rate); those values are assumed to be the very worst case (i.e., vehicle drivers will report unacceptable losses in driveability well before this point).

catalyst systems to provide better fuel economy and/or performance than oxidation catalyst systems with increased EGR and timing retard, on an average vehicle.

This inference is substantiated by engineering logic. With a three-way reduction catalyst, significant NOx control takes place in the exhaust system. This strategy reduces the need for NOx control in the combustion chamber (i.e., reduces the need for alteration of the combustion process itself). This permits the amount of EGR and the ignition timing to be calibrated to optimize engine performance (fuel economy, driveability, etc.), and not to be calibrated to a large extent for NOx emission control purposes. Some EGR is usually advantageous in conventional gasoline-fueled engines (see Figure 2-2); beyond this level of EGR, however, a three-way catalyst system will provide more fuel efficient NOx control with better vehicle driveability than increased EGR (at constant air/fuel ratio and ignition timing). When one also considers the enhanced calibration, engine control, and precise fuel metering made possible by the electronics used in closed-loop three-way systems, the fuel economy advantage of a three-way system should be even greater. Indeed, the additional electronics probably contribute more to enhanced fuel economy than the deletion of excess EGR, considering the relative size of the fuel economy tradeoffs presented in Figure 2-2. If these relative tradeoffs are representative, then the ultimate determinant of maximum EGR is likely its effect on vehicle driveability and performance.

As can be seen in Table 2-7, both the interpretations of current product mix and engineering logic are not at face value substantiated by available test data: fuel economies for the three-way equipped vehicles appear lower than those of non-three-way vehicles. (It is assumed that all vehicles deliver commercially acceptable driveability and performance.) However, there are significant vehicle differences aside from emission control systems which must be taken into account before relative fuel economies can be accurately compared.

Referring again to Table 2-7, the vehicle difference between the three-way and non-three-way fleets, in all cases, made the three-way technology appear less fuel efficient than it actually is. For example, the three-way fleet is, on average, heavier than the non-three-way fleet. Because heavier vehicles require more energy to move over the road, they are less fuel efficient. Also, the road load horsepower (hp) (i.e., the power required to overcome rolling resistance and aerodynamic drag while the vehicle moves at a constant 55 mph over smooth, level road) is higher for the three-way fleet (14.7 hp vs. 13.9 hp), again lowering its measured fuel economy.

Perhaps the most important difference between the two fleets is the difference in average engine displacement (3.49 liters vs. 3.07 liters). Greater displacement gives engines more reserve power, as one would expect to find in engines used in heavier vehicles. This reserve power, however, is costly: higher displacement engines run less efficiently, all other factors being equal. (At the typical cruising road loads observed in both the FTP and on-road operation, an engine will operate at some fraction of its maximum available power. For a gasoline engine, this means that the inlet air flow is throttled and that the engine is using more energy to pump air into the combustion chambers. For this reason, Otto cycle engines are more efficient at wide-open throttle (assuming constant air/fuel ratio and engine speed) where pumping losses are minimum. The greater the engine displacement, however, the more air throttling is required at a given road load horsepower and engine speed. This higher throttling makes the engine work harder to deliver the same amount of output power, and hence, is less efficient.)

This throttling effect also comes into play when the fleet engine rpm/vehicle speed (N/V) ratios are considered. (The N/V ratio is determined by the amount of speed reduction designed into a vehicle's transmission and rear axle gears.) For a given road speed, vehicles whose engines are turning faster (i.e., have higher N/V ratios) are less fuel efficient. This is due to more energy being required to pump engine intake air at a higher speed, and also due to increased frictional losses associated with higher speed. (These losses are, to some extent, reduced by an engine's propensity to lose less energy at higher speeds through heat transfer.) Again, the higher N/V ratios of the three-way fleet reduce its measured fuel economy. When all of these fleet differences are taken into account (i.e., when the fleet fuel economy is corrected to a value which would be seen if all vehicle parameters between fleets were identical), the true relative fuel economies of the three-way and non-three-way technologies can be compared.

Correction factors have been developed from EPA's certification and fuel economy data bases to allow a direct comparison of emission control system fuel economies despite dissimiliarities in vehicle parameters.[7,8] These correction factors are used by this analysis and the results of this correction exercise are presented in Table 2-8. When vehicle and engine displacement effects on measured fuel economy are eliminated, three-way vehicles are indeed found to be more fuel efficient at the 2.3 g/mile standard than non-three-way vehicles. This confirms our earlier interpretation of the manufacturers' product mix, i.e., that some tangible benefit is received from the additional investment in three-way systems at

Table 2-8

Corrected and Uncorrected Vehicle Data
For 1984 LDGTs

	EPA City mpg	Disp.	Equivalent Test Weight (lbs)	Road Load hp	N/V Ratio
Non-Three-Way Vehicle Average	19.4	3.07	3,740	13.9	41.9
Corrected* Non-Three-Way Vehicle Ave.	17.1	3.49	3,891	14.7	43.6
Actual Three-Way Vehicle Average	18.5	3.49	3,891	14.7	43.6
Percent Difference (actual three-way relative to corrected non-three-way):	+8.2%				

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* The correction equation, adapted from Reference 7 (for ETW, hp, and N/V) and from Reference 8 (for displacement), is:

$$\frac{\text{Corrected mpg} - \text{mpg}_{\text{old}}}{\text{mpg}_{\text{old}}} = -.589\left[\frac{\text{CID}_{\text{new}} - \text{CID}_{\text{old}}}{\text{CID}_{\text{old}}}\right] -.441\left[\frac{\text{ETW}_{\text{new}} - \text{ETW}_{\text{old}}}{\text{ETW}_{\text{old}}}\right]$$

$$-.209\left[\frac{\text{HP}_{\text{new}} - \text{HP}_{\text{old}}}{\text{HP}_{\text{old}}}\right] -.188\left[\frac{\text{N/V}_{\text{old}} - \text{N/V}_{\text{new}}}{\text{N/V}_{\text{old}}}\right]$$

Where mpg_{old}, CID_{old}, ETW_{old}, HP_{old}, and N/V_{old} are non-three-way parameters and ETW_{new}, CID_{new}, HP_{new}, and N/V_{new} are three-way based parameters. Corrected mpg is thus the fuel economy non-three-way vehicles would exhibit if their CID, ETW, HP, and N/V parameters were the same as those in three-way vehicles, i.e., if the only difference between the vehicles were the emission control system.

a 2.3 NOx standard. This result is also consistent with engineering logic. At any NOx standard at or below 2.3 g/mi, a three-way catalyst system should be inherently more fuel efficient and/or give better performance for the "average" LDGT. Based upon the above analysis, the current three-way LDGT fleet exhibits NOx emissions 40-50 percent less than the non-three-way fleet, and would simultaneously get about eight percent better fuel economy than identical vehicles equipped with non-three-way technology.

This leads us to an evaluation of the net fuel economy effects associated with a 1.2 NOx standard, assuming the product mix presented in Table 2-4. This evaluation is summarized in Table 2-9, which weights the expected fuel economy changes for each potential technology with the expected market share for each technology. Taking into account the worst case and most likely fuel economy penalties and benefits associated with our projected manufacturers' product mix, a fleetwide fuel economy benefit should be realized through compliance with the 1.2 g/mi NOx standard. Our analysis indicates that this would probably represent a 2-4 percent improvement in overall fleet fuel economy.

4. LDGT Summary

A 1.2 g/mi NOx standard for 1987 LDGTs is easily feasible. Many 1984 LDGTs are today using the required technology and exhibit emissions at or below 1987 target levels. The entire class of LDGVs have been meeting an essentially equivalent NOx standard with the same technology since 1981.

The fuel economy impact of this standard on LDGTs is dependent upon the manufacturers' individual choices in establishing product mix. However, our analysis indicates very little likelihood that a fuel economy penalty will be observed on a fleet-wide basis. Based upon available data, a fleetwide fuel economy benefit of 2-4 percent may result.

C. Light-Duty Diesel Trucks (LDDTs)

1. Low-Mileage Target Derivation

The low-mileage NOx emission target for LDDTs is derived using the same methodology used for LDGTs. Based upon the 1987 certification data in Table 2-10, a full-life low-mileage target range of .9 to 1.1 g/mi NOx is necessary to comply with a standard of 1.2 g/mi. (This target range was derived assuming an AQL factor range of 1.1-1.3,* and a calculated full-life multiplicative DF of 1.007.)

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* Again, the imprecision involved in using a range of AQL factors will be shown to be immaterial to this analysis' assessment of technological feasibility.

Table 2-9

Fuel Economy Implications of a 1.2 g/mi NOx Standard for 1987 LDGTs

1984 Emission Control System[1]	Projected 1987 Emission Control System[1]	Other Changes	Percent of Total LDGE Sales	Fuel Economy Effect	Magnitude of Fuel Economy Effect	
					Worst Case	Likely
3WY-CL	3WY-CL	None	15%[2]	None	0%[3]	0%[3]
3WY-CL	3WY-CL	Increased EGR, recalibration	16%[2]	Penalty	-10%[4]	-5%[4]
3WY-OL	3WY-CL	Calibration optimization	11%	None	0%[5]	0%[5]
3WY-OL	3WY-OL	Increased EGR, recalibration	0-.7%	Penalty	-10%[4]	-5%[4]
OX-CAT	3WY-OL	Calibration optimization	3%	Benefit	+8.2%[6]	+8.2%[6]
OX-CAT	3WY-CL	Calibration optimization	49-55%	Benefit	+8.2%[6]	+8.2%[6]
OX-CAT	OX-CAT	Increased EGR, recalibration	0.2-5%	Penalty	-6%[7]	-6%
		Sales-Weighted Fuel Economy Change:			+2 to 3%,	+3 to 4%

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[1] From Table 2-4.

[2] Assumes that 50 percent of 1984 LDGT 3WY-CL configurations meet the 1.2 NOx standard with absolutely no effort; the remaining 50 percent have emissdions above 1.2 (see Table 2-2) and are assumed to require further non-catalyst NOx control (i.e., increased EGr and timing retard).

[3] No emission control system changes are projected; hence, no fuel economy effect is projected.

[4] A 10 percent penalty is considered an absolute worst case value (see Figures 2-1 and 2-2); the 5 percent penalty is judged to be more likely for an "average" vehicle, representing the penalty observed with EGR induced NOx reductions of 50 percent from the NOx level seen at the most fuel efficient EGR calibration.

[5] Minimal fuel economy benefits are presumed attributable to the adoption of closed-loop technology; NOx reductions are attributable to more efficient reduction catalyst operation. This is a very conservative estimate, whereas it ignores the likely significant improvements attributable to the addition of electronic engine controls.

[6] From Table 2-8.

[7] A 5-7 percent penalty is judged the most severe any manufacturer would accept; if the penalty were higher, closed-loop and/or three-way technology would be adopted.

Table 2-10

Certification Data for 1984 LDDTs

Manufacturer	Engine Family	Emission Control System**	Half-Life NOx DF	Low-Mileage NOx (g/mi)
Small Engines With EGR:				
Isuzu	ESZ137K6JBD2	EGR	.968	.85
Isuzu	ESZ137K6JBD2	EGR	.968	.76
Mitsubishi	EMT2.3K6JCA3	EGR	.946	.78
Mitsubishi	EMT2.3K6JCA3	EGR	.946	.67
Toyota	ETY2.4K6JCC2	EGR,OTR	.976	.76
			Average:	.76
Small Engines Without EGR:				
Ford	EFM2.2K6JAG6	EM	.992	1.18
GM	E1G2.2K7ZZ97	EM	.948	2.08
GM	E1G2.2K7ZZ97	EM	.948	2.03
Grumman-Olsen	EGR1.6K6JAA5	EM	1.000	1.23
Grumman-Olsen	EGR1.6K6JAA5	EM	1.000	1.03
Isuzu	ESZ137K6JCD4	EM	.948	1.73
Isuzu	ESZ137K6JCD4	EM	.948	1.72
Nissan	ENS2.5K6JAF6	EM	1.021	1.50
Mitsubishi	EMT2.3K6JFD1	EM	1.002	1.54
Mitsubishi	EMT2.3K6JFD1	EM	1.002	1.57
Toyo Kogyo	ETK2.2K6JCS1	EM	.992	.85
Toyo Kogyo	ETK2.2K6JCS1	EM	.992	.83
Toyo Kogyo	ETK2.2K6JFR3	EM	.992	1.20
Toyota	ETY2.4K6JFF0	EM	1.003	1.56
			Average:	1.43
Large Engines:				
GM	E1G6.2K7ZZ41	EGR	1.012	1.85
GM	E1G6.2K7ZZ41	EGR	1.012	1.81
GM	E1G6.2K7ZZ74	EGR(elec.)	1.012	1.79
GM	E1G6.2K7ZZ74	EGR(elec.)	1.012	1.32
	Average (all LDDTs):		1.003***	1.33

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* Some engine families are duplicates, but represent the same engine family in a different vehicle configuration.

** EGR = Exhaust Gas Recirculation
EM = Engine Modification
OTR = Other

*** All DFs less than 1.000 are assumed to be 1.000 for purposes of average DF calculation.

2. Current LDDT Emission Levels (small engines)

With respect to emissions, the LDDT fleet is best discussed in two separate groupings: 1) those vehicles with an ETW below 4,000 lbs, and 2) those with an ETW above 3,999 lbs or with a GVW above 6,000 lbs. The majority of LDDT engine families are of smaller displacement and are found in the lighter vehicles; indeed, only a single engine model, GM's 6.2-liter engine, is currently found in the heavier vehicles. (The 6.2-liter engine, however, represents about 60 percent of total LDDT sales; its unique market niche and its high sales make it an important engine family to consider. Also, given its popularity, other similar engines are likely to follow.) Thus, the current LDDT class could be split semantically either by ETW/GVW or by engine displacement. For convenience, reference to engine displacement (i.e., small vs. large will be used here).

For these lighter vehicles, another segmentation is necessary to properly evaluate NOx emissions performance. This is accomplished in Table 2-10, where engines are grouped by emission control system. (The 6.2-liter engine families are also included for completeness.) As is readily apparent, all small engines equipped with EGR have current NOx emissions below the 0.9 to 1.1 g/mi target range. These are California vehicles meeting a 1.0 g/mi NOx standard. These families all have Federal counterparts which are not equipped with EGR, and whose emissions lie well above the 1.2 g/mi NOx emission level, as do the emissions of the majority of other small engines not equipped with EGR. This data substantiates the ability of EGR to reduce NOx emissions, and also leads one to conclude that all small LDDT engines, if equipped with EGR, could also meet a 1.2 g/mi NOx standard. The engine and vehicle size of those small LDDTs at or below 0.9 g/mi NOx are representative of the small LDDT fleet.

This conclusion is supported by the presentation in Table 2-11. Again, small displacement LDDT engines are segmented by emission control technology, but a clearer distinction is made between those engines not equipped with EGR on a Federal basis (but equipped with EGR in their California counterparts), and between those remaining non-EGR engines. By equipping virtually identical engines with EGR, NOx emissions were reduced, on the average, from 1.62 to .76 g/mi--a reduction of 53 percent. As can also be seen in Table 2-11, the remaining small engines without EGR would not need as great a reduction to comply with a 1.2 g/mi NOx standard. At worst (i.e., assuming the lower end of the target range would need to be met), emission reductions of 0 to 40 percent would be required; on the average a modest reduction of 20 percent (1.12 g/mi to

Table 2-11

Direct Comparison of Vehicle Data for Similar 1984 LDDT Engine Families

Manufacturer	4K NOx	4K HC	EPA City mpg	Displacement (liters)	Equivalent Test Weight (lbs)	Road Load hp	N/V
Small Engines with EGR							
Isuzu	.85	.28	34.6	2.25	3,125	10.8	43.6
Isuzu	.76	.36	30.9	2.25	3,375	13.0	55.0
Mitsubishi	.78	.19	27.8	2.30	3,500	13.5	42.5
Mitsubishi	.67	.16	31.2	2.30	3,125	11.4	42.5
Toyota	.76	.13	33.1	2.40	3,125	12.0	45.5
Average:	.76	.22	31.5	2.30	3,250	12.1	45.8
Similar Small Engines Without EGR*:							
Isuzu	1.73	.23	30.6	2.25	3,375	13.0	55.0
Isuzu	1.72	.22	30.3	2.25	3,125	10.8	56.1
Mitsubishi	1.54	.09	30.1	2.30	3,500	13.5	42.5
Mitsubishi	1.57	.15	32.1	2.30	3,125	11.4	41.5
Toyota	1.56	.12	31.5	2.40	3,625	13.8	46.0
Average:	1.62	.16	30.9	2.30	3,350	12.5	48.2
Other Small Engines Without EGR:							
Ford	1.18	.27	32.4	2.20	3,375	11.0	52.0
Grumman-Olsen	1.23	.26	35.3	1.60	2,375	12.7	51.8
Grumman-Olsen	1.03	.24	40.4	1.60	2,375	13.7**	39.3
Nissan	1.50	.23	33.6	2.50	3,250	11.4	42.6
Toyo Kogyo	.85	.16	31.4	2.20	3,250	12.5	46.0
Toyo Kogyo	.83	.14	32.5	2.20	3,125	12.5	46.0
Toyo Kogyo	1.20	.12	33.1	2.20	3,250	12.5**	45.7
Average:	1.12	.20	34.1	2.07	3,000	12.5	46.2

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* Non-EGR engine families which have a counterpart engine equipped with EGR.

** Value assumed (actual data unavailable).

0.9 g/mi) is necessary. As demonstrated by three families (five vehicle configurations), these percentage reductions are well within the capability of existing EGR systems.

Three potential tradeoffs are typically associated with diesel EGR: increased HC emissions, decreased engine durability, and decreased fuel economy. (A fourth tradeoff, increased particulate, is not discussed here; it will be presented at the end of the section addressing the 1.7 g/mi NOx standard for heavier LDTs.)

With respect to HC, there appears to be very little likelihood that the 0.8 g/mi HC standard will be exceeded. Of the engines already equipped with EGR, HC increased by 38 percent relative to their non-EGR counterparts, but at levels still well below the 0.8 standard. (For example, HC increased from 0.16 to 0.22 g/mi, on the average; HC emissions of the highest emitting EGR-equipped engine were only 0.36 g/mi.) Assuming the worst case scenario, that a 38 percent increase in HC would occur on the highest emitting of the remaining small engines in Table 2-11 (i.e., the Ford 2.2-liter engine experienced an increase in HC from 0.27 to 0.37 g/mi), compliance with the 0.8 g/mi HC standard is still assured. Although small HC tradeoffs are expected, they should in no way jeopardize compliance.

As for engine durability, the major concern lies with the effect of recirculated exhaust particulate on turbochargers and on the lubricating qualities of the engine oil. Since no current LDDT is equipped with a turbocharger, this aspect of the problem does not exist. With respect to engine oil, more frequent oil change intervals are the simplest solution to potential oil degradation problems. However, some engines are already equipped with EGR and, to EPA's knowledge, are not experiencing decreased durability, nor utilize shorter oil change intervals. At any rate, oil degradation, if observed at all, is a problem easily dealt with using techniques already developed for LDDV NOx control.

To assess the fuel economy impact of EGR on these engine families, an analysis similar to that performed on LDGTs is necessary. In short, a direct comparison is made of those engine families with and without EGR, and when all vehicle-to-vehicle differences are eliminated, the differential fuel economies are assumed to be attributable to the increased emission control. This is presented in Table 2-12. Unlike LDGTs, however, two of the correction terms (i.e., those for engine displacement and N/V ratio) may be somewhat inappropriate for diesel engines.* Since diesel engines are unthrottled, i.e., have high volumetric efficiencies at all

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* The correction factors were developed from EPA's certification data base, which is overwhelmingly comprised of gasoline-fueled vehicles.

Table 2-12

Corrected and Uncorrected Vehicle Data For Specific 1984 LDDTs

	EPA City mpg	Equivalent Test Weight	Road Load hp	N/V Ratio
Non-EGR Engine Average*	30.9	3,350	12.5	48.2
Corrected** Non-EGR Engine Average	31.5-31.8***	3,250	12.1	45.8
EGR Engine Average	31.5	3,501	12.1	45.8
Fuel Economy Penalty Attributed to NOx Emission Control:	0-1%			

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* From Table 1-11.

** Corrected using the equation from Reference 7:

$$\frac{mpg_{new} - mpg_{old}}{mpg_{old}} = -.441\left[\frac{ETW_{new} - ETW_{old}}{ETW_{old}}\right]$$

$$- .209\left[\frac{HP_{new} - HP_{old}}{HP_{old}}\right] - .188\left[\frac{N/V_{new} - N/V_{old}}{N/V_{old}}\right]$$

*** The range in corrected mpg values was derived by first excluding the N/V correction, and then including the N/V correction (see text).

loads, much of the increased pumping losses seen in throttled gasoline engines due to larger displacement or higher engine speeds (at constant road load) are not observed in diesel engines. Since Table 2-12 only compares similar engines, however, the issue of displacement disappears. As for N/V ratio, since engine friction increases with increasing engine rpm, at least some fraction of the N/V correction is appropriate; for estimation purposes, the N/V correction is both included and excluded in our total correction, yielding the maximum and minimum likely corrections. The results of this direct comparison in Table 2-12 indicate that, in achieving 53 percent reductions in NOx, vehicle fuel economy decreased 0-1 percent. When one considers that the remaining small LDDT engine families require, on the average, only about 20 percent reductions in NOx to meet a 1.2 standard, the fuel economy impact of the commensurately smaller amount of EGR should be negligible. In summary, the entire fleet of small Federal LDDTs--representing about 40 percent of projected 1984 Federal sales--should experience no measurable fuel economy penalty on account of the 1.2 g/mi NOx standard.

3. General Motors' 6.2-Liter Engine

As can be seen in Table 2-13, GM's 6.2-liter engine is found in LDDTs almost twice as heavy as those of other LDDT engine families. The 6.2-liter engine is already equipped with EGR, and in their California family, with electronically controlled EGR. In the heaviest vehicles (6,000 lbs ETW), the 6.2-liter engine will require nearly a 40-50 percent reduction in NOx emissions (from 1.8 to 0.9-1.1) to comply with the 1.2 g/mi standard. In the lighter vehicle (5,000 lbs ETW), NOx levels of 1.32 have already been achieved with electronically controlled EGR (see below). For this particular engine and its various vehicle configurations (representing 60 percent of projectd 1984 Federal sales), the feasibility of a 1.2 NOx standard depends upon the ability of the 6.2-liter engine, through either increased EGR, injection timing retard, or other engine modifications, to achieve the required NOx reductions without unacceptably compromising engine performance or other emissions.

Typically, diesel engines, because of their inherently lean heterogeneous combustion, are capable of tolerating larger amounts of EGR than conventional* gasoline-fueled engines.

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* "Fast-burn" combustion chambers can substantially improve the EGR tolerance of gasoline-fueled engines, although this technology has yet to be widely adopted even among passenger cars.

Table 2-13

Vehicle Data For 1984
GM 6.2L LDDT Engine Families

GM 6.2L Engine	4K NOx	4K HC	EPA City mpg	Equivalent test weight (lbs)	Road Load hp	N/V
EGR	1.85	.22	18.2	6,000	15.1	31.4
EGR	1.81	.33	17.8	6,000	15.1	28.8
EGR (electronic)	1.79	.27	17.6	6,000	15.1	31.4
EGR (electronic)	1.32	.18	21.0	5,000	17.2	24.5
Average	1.69	.25	18.7	5,750	15.6	29.0

Since the smooth and fast propagation of a flame front in gasoline engines is impaired by too much oxygen-deficient EGR, there is a limit to the amount of EGR gasoline-fueled engines can accept before performance suffers. On the other hand, diesel engines run very lean (oxygen rich), and even large amounts of EGR fail to dilute the oxygen sufficiently to impair turbulent heterogeneous combustion at lighter engine loads.

Above some level of EGR, however, even diesel engine performance is impaired. This can be inferred from Figure 2-3, in which the effect of EGR on several parameters is plotted for a small (2.2-liter) diesel engine. As fuel flow is increased (i.e., as the air/fuel ratio becomes less and less lean, and less oxygen becomes available for any given fuel droplet), a point is reached beyond which more EGR penalizes fuel consumption, and drastically increases HC and smoke emissions. Quite simply, complete combustion is being impaired. The same effects would be observed at lighter engine loads (i.e., lesser fuel flows) if even more EGR were added. Again, the major mechanism is the reduction of the amount of oxygen relative to the amount of fuel to be burned.

From the above discussion, it can be deduced that at lighter engine loads a greater percentage of EGR can be tolerated because of the greater amount of excess oxygen. Indeed, this is typically observed in EGR calibrations - as the load is increased, the relative percent of EGR decreases. This is in fact the calibration scheme for GM's 6.2L engine (see Figure 2-4).[14] In almost all cases, this calibration is maintained by simple mechanical means, e.g., by mechanically controlling EGR flow as a function of throttle position. However, mechanical control systems are not capable of precisely controlling EGR systems to predetermined optimum mode-specific* calibrations; only a general calibration is possible. For this reason, electronic control systems are far more effective than mechanical systems because of their potential for monitoring more than one control parameter (e.g., throttle position, engine speed, and EGR valve control vacuum), and their ability to set the optimum EGR flow for predetermined combinations of control parameters. The 1984 California version of the 6.2L diesel is equipped with electronically controlled EGR of this type. For this particular engine, GM stated that "with more stringent NOx standards, the requirement for optimization of the inverse NOx/particulate relationship can be achieved by the electronic EGR control system."[14]

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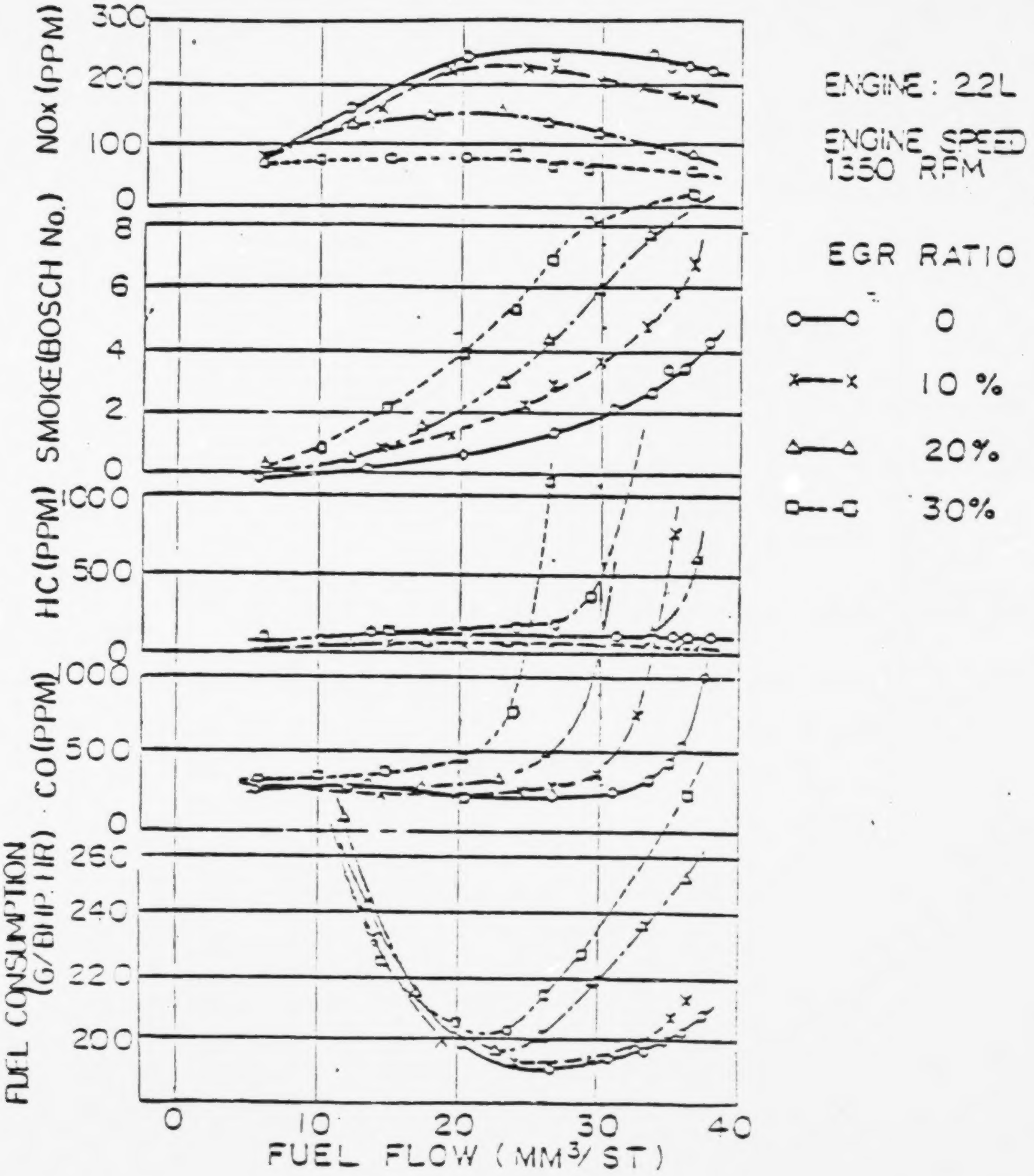
* As determined by specific modes observed over the applicable test cycle.

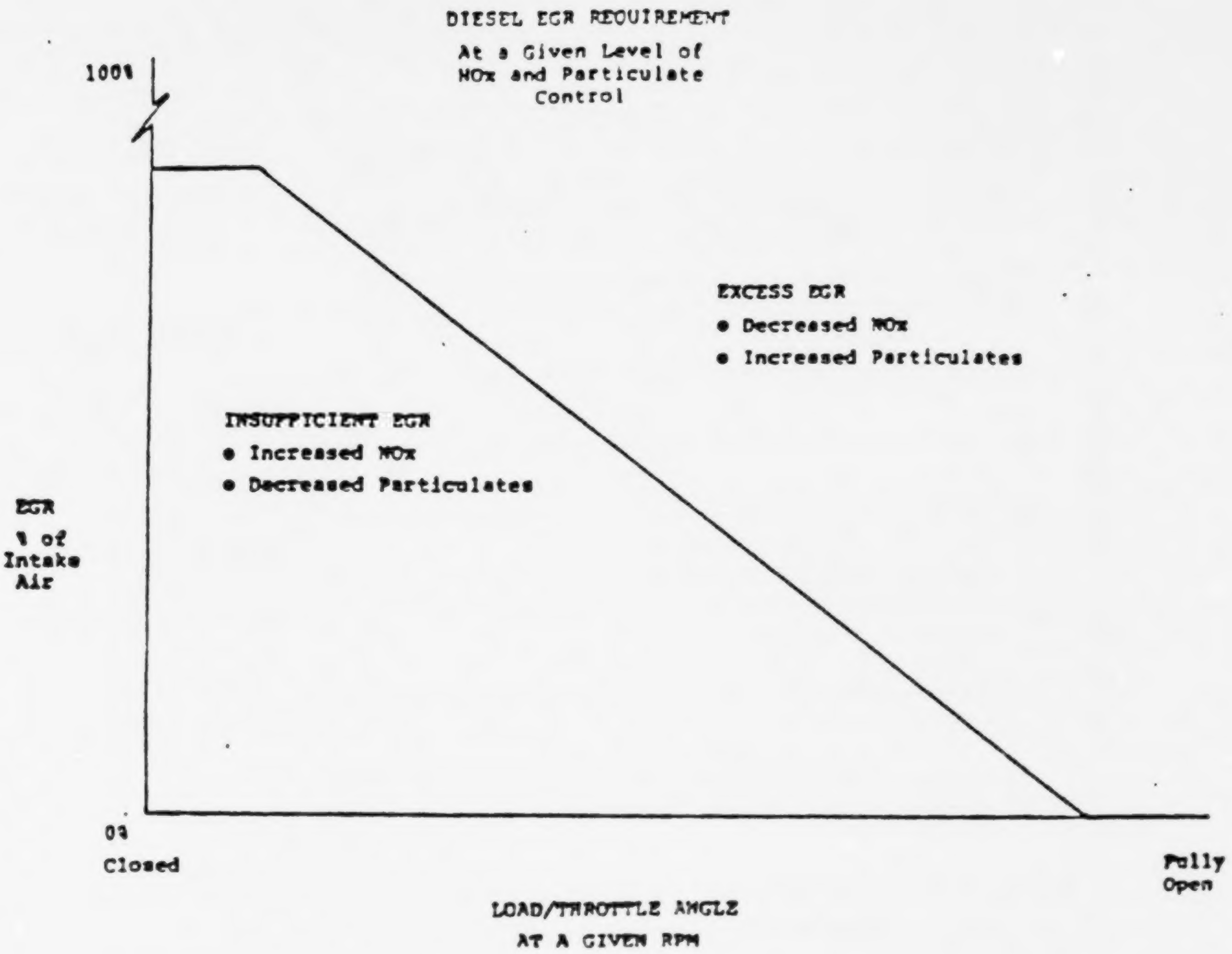
Figure 2-3

EFFECT OF EGR ON HC, CO, NOx, SMOKE EMISSIONS & FUEL CONSUMPTION



(Taken from Reference 13)

Figure 2-4



(Taken from Reference 14)

(The applicable 1984 California NOx standard is 1.5 g/mile.) This mode specific NOx control maximizes NOx reductions while minimizing adverse tradeoffs.

Since GM's 6.2L engine in California is already equipped with electronic EGR, the main question to be addressed at this point is whether or not NOx emissions can be further reduced to permit compliance with a 1.2 g/mile NOx standard. To answer this directly, one would need to determine whether or not the EGR rate could be increased. Sufficient information about this engine does not exist to make this determination. Thus, more indirect means must be used.

This alternate approach compares the stringency of the 1.2 g/mi NOx standard for the 6.2L engine to that of the 1.0 g/mi NOx standard for GM's largest LDDV engine, the 5.7L. Large LDDVs with this engine meeting the 1985 1.0 g/mi Federal NOx standard provide the closest analogy to the compliance of the 6.2L engine to a 1.2 g/mi NOx standard. The primary differences in the two situations is that the LDDT is heavier and boxier than the LDDV and requires more power to operate over the EPA city cycle, thus producing more NOx emissions.

It can reasonably be assumed that the increase in NOx emissions is proportional to the amount of fuel consumed over the cycle (or inversely proportional to fuel economy). Engine testing has shown NOx emissions to be relatively constant on a brake-specific basis over a wide variety of cycles. Given that LDDV and LDDT engines have the same basic designs and, thus, the same efficiencies, NOx emissions that were constant on a brake-specific basis would also be constant on a fuel-specific basis. Thus, the relationship between LDDV and LDDT NOx emissions can be approximated by the following equation:

$$\text{NOx (LDDT)} = \frac{\text{mpg (LDDV)}}{\text{mpg (LDDT)}} \cdot \text{NOx (LDDV)}$$

The worst city fuel economy for an LDDT using the 6.2L engine is 17.6 mpg (see Table 2-13). The worst fuel economy for a 1985 LDDV powered by the 5.7L engine is 20.6 mpg. (Worst case fuel economies are appropriate since in each case they represent the most difficult compliance task.) Thus, LDDT NOx emissions can be expected to be approximately 17 percent greater than LDDV NOx emissions. The LDDV NOx value could simply be taken to be the 1.0 g/mi standard. However, this is half-life standard and the projected LDDT result would be on a half-life basis. Thus, to yield an equivalent full-life LDDT NOx level, the LDDV NOx standard should be put on a full-life basis. This means adjusting it for an additional 70,000 miles of NOx deterioration. Using the full-life (120,000 miles) DF of 1.007 estimated previously, the last 70,000 miles should account for an additional DF of 1.004. As can be seen, however, this adjustment is negligible and will be ignored. Also, since the SEA requirements for LDDVs are the same as those for LDDTs, the SEA factors can be ignored and the two NOx standards can be compared directly. Thus, the 17 percent greater fuel consumption of the 6.2L engine should produce 17 percent greater NOx emissions and a standard of 1.17 g/mi NOx should be achievable. As this is slightly below 1.2 g/mi, one can conclude that the same technology which will allow the 5.7L engine to comply with a 1.0 g/mi NOx standard in 1985 should provide compliance with a 1.2 g/mi NOx standard in 1987. Of course, this is an approximation since there are other more subtle differences between LDDVs and LDDTs. However, it provides a strong indication that a 1.2 g/mi NOx standard is achievable.

The effect of meeting the 1.2 g/mi NOx standards on fuel economy and particulate emissions will not be addressed here. These topics will be addressed at the end of the following discussion of the feasibility of the 1.7 g/mi standard for heavier LDDTs.

4. LDDT Summary

For 40 percent of total LDDT sales, i.e., those engine families of smaller displacement in the lighter vehicles, compliance with a 1987 NOx standard of 1.2 g/mi should be easily feasible. EGR will be necessary in probably all but one engine family to permit compliance and, overall, any fuel economy penalty should be negligible. The demonstration of technological feasibility for the GM 6.2L engine (i.e., larger LDDTs) is less straightforward; feasibility depends on extrapolation of data from large LDDVs. However, all indications point toward the 1.2 g/mi standard being feasible for these large LDDTs.

D. 1.7 g/mi NOx Standard for Heavier LDTs

There are three reasons for considering a 1.7 g/mi NOx standard for heavier LDTs. First of all, while apparently feasible, a 1.2 g/mi NOx standard for heavier LDDTs will affect the stringency of the 0.26 g/mi particulate standard, primarily the number of vehicles requiring trap-oxidizers to meet the standard. Secondly, while a 1.2 g/mi NOx standard is clearly feasible for heavier LDGTs, a more stringent NOx standard for LDGTs than LDDTs would economically encourage the purchase of LDDTs, which the Agency does not wish to do. Thus, equivalent standards are desirable. Thirdly, 1995 LDT NOx emissions can be maintained at current levels with a 1.7 g/mi NOx standard for heavier LDTs, gasoline-fueled and diesel.

In splitting the LDT class at 4,000 lbs ETW and 6,000 lbs GVW, EPA is following the precedent already set by California and the Clean Air Act. There is also a natural break in LDT sales at this point, particularly for diesels.

The LDT engine families certified in vehicle configurations over 3,999 lbs ETW are presented in Table 2-14. Also presented are current emission control systems, and projections (and assumptions) for likely compliance strategies for a 1.7 standard.

The analysis presented in Table 2-14 is easily summarized. For LDGTs, a 1.7 standard still appears to require the majority of engine families to adopt closed-loop three-way technology, though a few additional oxidation catalyst equipped families should be able to remain non-three-way. However, since less severe engine calibrations are necessary, there is the potential for significant (5-10 percent) fuel economy improvements for selected vehicles. At the same time, a couple of familes could see a decrease in fuel economy by avoiding a change to closed-loop, three-way technology. However, this would be the manufacturer's choice to trade-off first cost and fuel economy. In any event, on a sales-weighted basis, no net fuel economy change is projected relative to a 1.2 g/mi standard. Relatively minor changes to fleetwide emission control system mix are expected relative to a 1.2 g/mi NOx standard; these are summarized in Table 2-15.

With respect to heavier LDDTs, the primary effect of a more relaxed NOx standard would be reduced EGR rates. Given that GM has already gone to electronics for California's 1.5 g/mi standard, electronics would still likely be used at 1.7 g/mi. Given this use of electronics, there should be no fuel economy penalty with respect to the current 2.3 g/mi standard (i.e., any penalty associated with the 1.2 g/mi standards should disappear).

This finding is confirmed by the LDDV data contained in Table 2-16. The fuel economies of these LDDV engine families are shown under various NOx standards. As can be seen, the fuel economy effect of either the 1.5 or 1.0 g/mi NOx is very small, and in no case more than one percent.

Table 2-14

Implications of a 1.7 NOx Standard for LDTs Over 4,000 Lbs ETW

Manufacturer	Engine Family[1]	Mean Equivalent Test Weight (lbs)	Low-Mileage NOx (g/mi)	Low-Mileage Targets for 1987 1.7 (g/mi)[2]	1984 Emission Control Systems	Projected Compliance Strategy for 1987 1.7 g/mi NOx Standards: Additions of Technology[3]	Projected Compliance Strategy for 1987 1.7 g/mi NOx Standards: Changes to Calibrations: EGR, timing[3]	Projected Compliance Strategy for 1987 1.7 g/mi NOx Standards: Incremental Fuel Economy Change Relative to 1.2 NOx Standard[4]
Gasoline Engines								
AMC	EAM258T2HEAX	4,250	1.17	1.0-1.2	EGR/PLS/3CL	None	None	+5%
	EAM258T2HEAX	4,500	1.79	1.0-1.2	EGR/PLS/3CL	None	Yes	+10%
	EAM360T2HLEX	4,750	1.27	1.0-1.2	EGR/PMP/3WY	None	Yes	0%
Chrysler	ECR3.7T1BBB0	4,500	1.61	1.2-1.4	EGR/PMP/OXD	3CL[5]	Yes	0%[5]
	ECR5.2T2BBF5	5,000	1.77	1.2-1.4	EGR/PMP/OXD	3CL	Yes	0%
	ECR5.9T4BAF9	5,250	1.37	1.2-1.4	EGR/PMP/OXD	None	None	-8%
Ford	EFM4.9T1HGG5	4,583	.72	1.0-1.2	EGR/PMP/OXD/3CL	None	None	0%
	EFM5.0T2GAF2	5,125	1.38	1.0-1.2	EGR/PMP/OXD/3WY	CL	Yes	0%
	EFM5.8T2HGG0	4,625	.69	1.0-1.2	EGR/PMP/OXD/3CL	None	None	0%
	EFM5.8T2HGG0	5,375	1.86	1.0-1.2	EGR/PMP/OXD/3CL	None	Yes	+10%
	EFM5.8T4GAF3	4,625	1.76	1.0-1.2	EGR/PMP/OXD/3WY	CL	Yes	+5%
GM	E1G5.7T4HHCX	4,750	1.61	1.2-1.4	EGR/PMP/OXD	3CL[5]	Yes	0%[5]
	E1G5.7T4HHCX	5,500	2.20	1.2-1.4	EGR/PMP/OXD	3CL	Yes	+5%
Dutton	EDN6.0T4HRAX	6,000	1.40	1.0-1.2	EGR/PMP/OXD/3CL	None	Yes	+5%
Toyota	ETY4.2T2AFF4	4,500	.99	1.2-1.4	EGR/PMP/OXD/OTR	None	None	0%
						Sales-Weighted Average[6]:		0%
Diesel Engines								
GM	E1G6.2K7ZZ41	6,000	1.83	1.3-1.5	EGR	Electronic EGR	Yes	0%
						Sales-Weighted Average[7]:		0%

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[1] Where significant differences in NOx emissions arise between configurations of the same family tested at different ETWs, all relevant ETWs are presented.

[2] Based upon full-life DFs of 1.286 (three-way catalysts), 1.070 (oxidation catalyst), and 1.007 (diesels), and an AQL range of 1.1-1.3; also based upon the technology in the 1984 vehicle.

[3] Judgments are made whether the addition of technology is needed to lower 1984 low-mileage NOx levels to 1987 target levels. In general, additions of technology are presumed necessary for any current three-way vehicle with NOx emissions greater than 1.3 g/mi, and for any non-three-way vehicle with NOx emissions greater than 1.5 g/mi. (The difference arises primarily from the difference in LMTs for the specific technologies.) Where technology changes are expected, or where technology changes are not expected but emissions must still be lowered to meet target levels, then recalibrations are assumed necessary.

[4] These values are drawn from Table 2-9. Note that the estimates are still conservative with respect to the addition of electronic controls: no fuel economy benefit is assumed where open-loop three-way systems are converted to closed loop.

[5] It is also possible that manufacturers would retain open-loop, oxidation catalyst technology for these vehicles. If so, then a fuel economy penalty of up to 8 percent could occ

Based upon manufacturers' confidential sales projections for [illegible]4.

[7] Sales-weighted for all LDTs, gas and diesel.

Table 2-15

Approximate Projected Market Shares of Emission Control Technologies for 1987 LDGTs Meeting NOx Standards of 1.7/1.2 g/mi

Technology	Market Share[1]
Non-Three-Way (open-loop)	1 - 10%
Three-Way (open-loop)	.7 - 3.7%
Three-Way (closed-loop)	86 - 98%

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[1] Derived from Tables 2-4 and 2-14. The major differences between these projections and those in Table 1-4 are that one additional engine family (AMC EAM360T2HLFX) will probably remain open-loop three-way, two additional families (Chrysler ECR3.7T1BBBO and GM F1G5.7T4HHCX), may remain open-loop non-three-way, and one family (Chrysler ECR5.9T43AF9) will probably remain open-loop non-three-way.

Table 2-16

Fuel Economy Effect of Various LDDV NOx Standards

Model Year	NOx Standard	EPA City MPG	Change in MPG
General Motors 5.7L Engine Family - Federal			
1980	2.0	19.90	
1981-82	1.5	19.85	-0.05 (0.3%)
Mercedes-Benz 3.0L Engine Family			
Non-Turbo - Federal			
1980	2.0	23.0	
1981	1.5	23.3	+0.3 (+1.3%)
Turbo - Federal			
1980	2.0	24.4	
1981-82	1.5	25.2	+0.8 (+3.3%)
Turbo - California			
1981-82	1.5	25.71	
1984	1.0	25.54	-0.17 (-.7%)
General Motors 4.3L Engine Family - California			
1982-83	1.5	24.14	
1984	1.0	23.98	-0.16 (-.7%)

The primary effect of the reduced EGR rates would be lower engine-out particulate emissions. This is important, because the 1987 particulate standard of 0.26 g/mi does not appear to be feasible without the use of trap-oxidizers on some vehicles. Given that particulate emissions averaging is allowed, any increase (or decrease) in engine-out particulate levels will increase (or decrease) the percentage of vehicles requiring trap-oxidizers to meet the particulate standard. While the full cost of meeting the 0.26 g/mi NOx standard was considered when the particulate standard was implemented, it is still appropriate to consider any incremental savings here of a 1.7 g/mi NOx standard since it is the direct result of the decision to propose a 1.7 g/mi NOx standard for heavier LDDTs.

The effect of the NOx standard on the percentage of trap-equipped LDDTs has been analyzed elsewhere.[2] Under a 1.2 g/mi NOx standard for all LDDTs, 41-56 percent of all LDDTs would require trap-oxidizers. With a 1.7 g/mi NOx standard for heavier LDDTs, roughly 16-24 percent of all LDDTs would require trap-oxidizers, a difference of 32-36 percent.

E. Summary: 1987 NOx Standards for LDTs

A 1.2 g/mi NOx standard appears feasible for all LDGTs and lighter LDDTs; some heavier LDDTs may experience some difficulty but the 1.2 g/mi standard should be feasible for these vehicles as well. Overall, a 1.2 g/mi NOx standard should result in a net fuel economy improvement for the LDT fleet, primarily due to the increased use of electronics.

For reasons of reduced engine-out particulate emissions and market equity, a 1.7 g/mi NOx standard is being considered for heavier LDTs. This standard is quite feasible for both heavier LDGTs and LDDTs.

III. Heavy-Duty Gasoline Engines (HDGEs)

A. Introduction

Unlike the majority of light-duty trucks, heavy-duty engines (HDEs) as a class, especially diesels, will encounter substantial technological difficulty in meeting the statutory NOx standard which represents a 75 percent reduction from uncontrolled levels, i.e., 1.7 g/BHP-hr. As is evident for the discussion in the following section (Section IV), no proven technology is available today, nor is expected to be available by 1990 which will allow heavy-duty diesel engines (HDDEs) to comply with a 1.7 g/BHP-hr standard. On the other hand, it is conceivable that heavy-duty gasoline engines (HDGEs) could meet a 1.7 g/BHP-hr standard using three-way catalyst technology.

(This possibility was extensively discussed in support documents to the January 19, 1981 ANPRM.)[15] However, if a single NOx standard for all HDEs is promulgated, then the ultimate determinant of NOx standard stringency in the near future must be the heavy-duty diesel engine.

This section will address the feasibility of both the 1987 6.0 g/BHP-hr and the 1990 4.0 g/BHP-hr emission standards for HDGEs. Current HDGE emission levels will be discussed as part of the analysis of the 1987 standard, as will the effects of leadtime constraints and available emission control technologies. The analysis for the 1990 standard will consider the likelihood of new and more refined emission control technologies. In both cases, fuel economy and performance implications of the standards will be considered.

B. Feasibility of a 1987 NOx Standard of 6.0 g/BHP-hr

In 1987, there will be two classes of HDGEs: catalyst-equipped and non-catalyst engines. Approximately 70 percent of HDGEs, those intended for use in most Class IIb and III vehicles, will be equipped with oxidation catalysts and will be complying with emission standards of 1.1 g/BHP-hr HC, 14.4 g/BHP-hr CO, and 10.6 g/BHP-hr NOx.* The remaining HDGEs will be complying with non-catalyst standards of 1.9 HC, 37 CO, and 10.6 NOx.**

All 1987 HDGE engines will likely be equipped with large dual air pumps for HC and CO control. Carburetor calibrations will be somewhat leaner than current technology engines at both part- and wide-open throttle. Combustion and exhaust system temperatures will be higher than those of current technology engines because of these leaner air/fuel ratios, and also because of increased post-combustion oxidation of partially burned fuel.[16] About 70 percent of 1987 HDGEs will be equipped with oxidation catalysts. Most 1985 and later model year HDGEs will also be equipped with at least some EGR. (Manufacturers have reportedly chosen to do this for two reasons: to standardize vehicles sold under different Federal and California NOx standards, and also in anticipation of a future Federal NOx standard.)[17]*

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* Based upon the MVMA HDGE transient test cycle.

** Also based upon the MVMA cycle. Some non-catalyst engines may also be certified on the EPA cycle prior to 1987, but for certification to the 1987 NOx standard, only an MVMA cycle-based standard will be provided, carryover notwithstanding.

As a first step in evaluating the feasibility of a 6.0 g/BHP-hr standard for 1987, the low mileage emission targets must be derived to account for both deterioration and production variability.

To account for deterioration, two very important points must be considered. First of all, for HDGE engines to-date, NOx deterioration has been reported to be typically minimal or non-existent. For example, 13 of 16 HDGE families certified in 1983 had additive NOx deterioration factors of 0.00; these 13 families include seven of the eight families certified with EGR. Therefore, for this analysis it will be assumed that an additive NOx deterioration factor of 0.00 will adequately characterize both the average oxidation catalyst and non-oxidation catalyst engine. Secondly, unlike the methodology used for LDTs, oxidation catalyst-equipped HDGEs will not be considered to have multiplicative NOx DFs for purposes of this analysis. Although contrary to standard methodology (i.e., vehicles with aftertreatment devices use multiplicative DFs and those without use additive DFs), this approach is consistent with engineering logic in the sense that oxidation catalysts (the aftertreatment device present) do not directly affect NOx emissions or their deterioration. The assumption also permits a single low-mileage target level to be derived for all HDGEs, rather than forcing the derivation of different target levels for engine families which will be equipped with catalysts.

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* Some NOx control is probably already in effect on current and prototype HDGEs. This is likely not so much because of the presence of EGR (manufacturers report that EGR flow rates for 1985 Federal calibrations will be minimal), but primarily because NOx levels have remained essentially constant despite the increased control of other pollutants. In particular, over the last twelve years HDGE HC and CO emission levels have decreased dramatically from uncontrolled levels, whereas NOx emissions have remained essentially constant (see Table 2-17). These dramatic reductions in HDGE HC and CO emissions have to some extent been achieved via leaner air/fuel ratios, a strategy which typically increases NOx (see Figure 2-5). (Leaner air/fuel mixtures promote higher maximum combustion temperatures, thereby promoting increased NOx formation.) Therefore, one would have expected HDGE NOx emissions to have increased somewhat as more stringent HC and CO standards went into effect. The fact that NOx emissions have remained essentially constant suggests that some degree of NOx control is already in effect.

Table 2-17

Heavy-Duty Gasoline Engine NOx Emission Trends

	Emission Levels (EPA transient cycle-based g/BHP-hr)			Applicable Emission Standards (g/BHP-hr) (EPA transient cycle-based g/BHP-hr)		
HDGE Model Year Technology	NOx	HC	CO	NOx	HC	CO
1969 (uncontrolled)*	6.1	12.7	155	-------None------		
1972-73 (uncontrolled NOx)*	6.9	6.8	116	None	275 ppm	1.5%
1979 (some HC/CO control)*	5.9	3.0	88	8.5-10**	1.5**	25**
1985-87 Prototype (significant non-catalyst HC/CO control)	6.0***	1.7***	26***	10.7	2.5	40

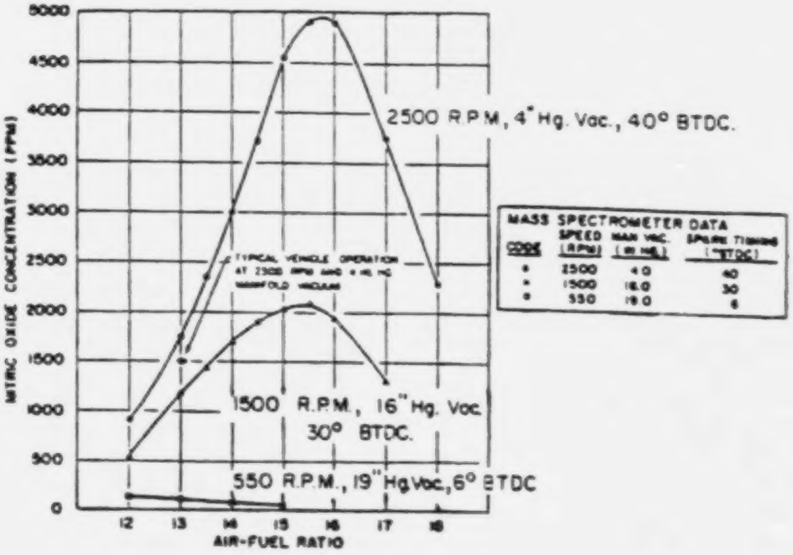
---

* Sales-weighted average.

** Based upon the 9-mode test. The NOx standard was actually an HC + NOx standard; the range 8.5 to 10 g/BHP-hr represents the possible range of NOx emissions for complying engines.

*** Arithmetic mean of available data from Table 2-18.

Figure 2-5



Effect of air-fuel ratio on exhaust NO concentrations for various speed-load combinations. (From Reference 12.)

With respect to production variability, no elaborate statistical derivation will be attempted here, primarily because reasonable estimates have been provided in the past. In response to earlier rulemakings,[18] Ford estimated non-catalyst HDGE 40 percent AOL factors of 1.2 for HC and 1.3 for CO, whereas GM estimated factors of 1.1 for all emissions. For purposes of this analysis, a mean value of these three estimates will be used (i.e., a NOx AOL factor of 1.2). This assumption presupposes that NOx emission variability from one engine to the next will be no larger than that of non-catalyst HC and CO. (In fact, NOx variability should be less than that of HC and CO because of the greater sensitivity of HC and CO emissions in gasoline-fueled engines to variations in calibration parameters.)

Using these estimates for deterioration and production variability, a low-mileage target of 5.0 g/BHP-hr for a 6.0 standard is derived. This target agrees closely with the estimate provided by Ford (4.9 g/BHP-hr) in their comments to the January 19, 1981 ANPRM. As will be seen, a precise estimate of the target level is not critical to the outcome of the analysis.

The second step in feasibility determination is to consider leadtime. In 1987, non-catalyst HDGEs will have last undergone certification to new standards in the 1985 model year. Two years of development time are thus available before recertification to a more stringent 1987 NOx standard, if recertification is necessary at all (i.e., carryover of low-emitting non-catalyst engine families may be possible). This two-year minimum time does not include development efforts undertaken prior to 1985; NOx control-related development activities actually began in 1981 in response to the ANPRM. Also, the combustion process in gasoline engines is well understood, and a wealth of relatable experience is available from LDV research.

However, NOx standards for HDGEs cannot be considered independently from other emission requirements. Substantial industry development efforts are already underway prior to 1987 as HDGE manufacturers prepare to equip the majority of their engines with oxidation catalysts to meet 1987 HC and CO standards. Promulgation of a new NOx standard for 1987 will require that NOx development work be added to this ongoing effort, especially that which requires interactive calibrations for HC, CO, and NOx control in the new catalyst-equipped engine families.

Obviously, some development testing has already been performed (as noted in the manufacturers' public comments to the January 19, 1981 ANPRM), and further development testing will no doubt be initiated during the course of this rulemaking, as well as that which will occur as a matter of course during the development of catalyst technology. However, the substantial ongoing development efforts and the leadtime situation for 1987 HC and CO control will limit the level of development effort, and hence the degree of NOx reductions, which can be accomplished by 1987 for HDGEs. Thus, somewhat less than the equivalent of two years leadtime is available for NOx control development. Because of this, it is unreasonable to expect major engine or hardware changes to be available for production within this timeframe. The analysis below takes this finding into account in assessing the degree of feasible NOx reductions.

The final step in feasibility determination, given the factors discussed above, is to evaluate the feasibility of the 6.0 g/BHP-hr standard if only easily achievable emission reductions from current levels are assumed feasible by 1987.

The latest available emission data for 1985 prototype HDGEs are presented in Table 2-18. Four of these eleven families already meet the target level associated with a 6.0 g/BHP-hr standard. As presented in Table 2-19, the remaining families will require reductions in NOx emissions from 7 to 34 percent; for the "average" engine family, a 15 percent reduction will be necessary. In short, to meet a 1987 6.0 g/BHP-hr NOx standard, only modest NOx reductions are required in only two-thirds of the fleet.

There are several proven emission control strategies available to reduce NOx emissions in the fraction of engine families which require reductions to meet a 6.0 g/BHP-hr standard in 1987. These emission control strategies, discussed at greater length below, do not involve the addition of new hardware or technologies to the engine. Rather, they involve optimization and recalibration of existing components. Specifically, they include optimization of ignition timing, EGR rates, and air/fuel ratio calibrations. In all cases, these strategies have already been applied to LDV, LDT, and HDG engines, and a large base of technical experience is available to guide development work. In fact, as illustrated in Table 2-20, Ford quickly achieved NOx levels below the target levels for the 1987 standard in their early development work in 1981.

For non-catalyst engine families, strategies as simple as rich air/fuel calibrations may be used for NOx control. Rich mixtures promote cooler combustion, thereby reducing NOx emissions. At the same time, the resulting increased engine-out HC and CO emissions must be afterburned in the

Table 2-18

1985-87 Non-Catalyst HDGE
Prototype Emission Levels[17]

Engine Family	NOx*	HC*	CO*
Ford 4.9L-1V	6.6 (6.5)	1.7 (1.2)	28 (25)
Ford 6.1L-2V	7.4 (7.3)	1.6 (1.1)	27 (23)
Ford 6.1L-4V	5.5 (5.4)	2.3 (1.7)	32 (29)
Ford 7.0L-4V	7.7 (7.6)	2.1 (1.5)	21 (18)
Ford 7.5L-4V	6.5 (6.4)	1.9 (1.4)	27 (24)
GM 292	6.8 (6.7)	2.2 (1.6)	25 (22)
GM 350-2V	6.1 (6.0)	1.6 (1.1)	28 (25)
GM 350-4V	5.1 (5.0)	2.0 (1.5)	27 (24)
GM 366	3.6 (3.4)	0.8 (0.4)	18 (15)
GM 454	4.3 (4.2)	1.0 (0.6)	22 (19)
IHC 345**	4.4 (4.6)	2.0 (1.5)	37 (29)
Arithmetic Mean:	6.0 (5.9)	1.7 (1.2)	26 (22)

---

* Emissions are expressed in g/BHP-hr, EPA cycle based. Numbers in parentheses are MVMA cycle based. The derived correlation between test cycles is:

HC: MVMA = .886 (EPA) - .318,

CO: MVMA = 1.03 (EPA) - 4.04, and

NOx: MVMA = 1.01 (EPA) - .193, as derived in Reference B.

These equations were used where emission results were available only in terms of one test cycle.

** 1980 California production version.

Table 2-19

Low Mileage NOx Emission Reductions From 1985-87 Prototype Levels** for Various NOx Standards

Engine Family	1985-87 Prototype NOx Level,** g/BHP-hr	Potential NOx Standards**, g/BHP-hr (associated target levels* are presented in parentheses)							
		3.0 (2.5)	4.0 (3.3)	5.0 (4.2)	6.0 (5.0)	7.0 (5.8)	8.0 (6.7)	9.0 (7.5)	10.7 (8.9)
Ford 4.9L-IV	6.5	-62	-49	-35	-23	-11	0	0	0
Ford 6.1L-2V	7.3	-66	-55	-42	-32	-21	-8	0	0
Ford 6.1L-4V	5.4	-54	-39	-22	-7	0	0	0	0
Ford 7.0L-4V	7.6	-67	-57	-45	-34	-24	-12	-1	0
Ford 7.5L-4V	6.4	-61	-48	-34	-22	-9	0	0	0
GM 292	6.7	-63	-51	-37	-25	-13	0	0	0
GM 350-2V	6.0	-58	-45	-30	-17	-3	0	0	0
GM 350-4V	5.0	-50	-34	-16	0	0	0	0	0
GM 366	3.4	-26	-3	0	0	0	0	0	0
GM 454	4.2	-40	-21	0	0	0	0	0	0
IHC 345***	4.6	-46	-28	-9	0	0	0	0	0
Arithmetic Mean:	5.9	-55	-39	-25	-15	-7	-2	0	0

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* Assuming an additive DF of 0.00, and an AOL factor of 1.2.

** MVMA cycle based, from Table 2-18.

*** 1980 California production version.

Table 2-20

Ford's Best-Effort HDGE
NOx Development Data in 1981 [17]**

Ford Engine Family	Emissions (g/BHP-hr)* HC	CO	NOx
6.1L-4V	3.15**	37.1	4.60
7.0L-4V	1.0	28.7	4.85
7.5L-4V	1.31	23.8	4.41

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* Non-catalyst, MVMA cycle based.

** Note that this data was submitted before substantial improvements in the HC and CO performance of this engine was achieved during 1982 and 1983 (see Table 2-19).

exhaust system. Increased air injection and stainless steel exhaust systems, as well as vehicle chassis designs to preclude overheating problems, are necessary. The drawback associated with this strategy, however, is an increase in fuel consumption associated with rich mixture calibrations. This strategy is nevertheless being used today in California for IHC's 345-CID family, data from which are presented in Tables 2-18 and 2-19. Note that this 1980 model year engine already meets MVMA cycle-based non-catalyst emission standards of 1.9 g/BHP-hr HC, 37.1 g/BHP-hr CO, as well as 6.0 g/BHP-hr NOx.

At this point, it should be stated that the presence of an oxidation catalyst should have little impact on the feasibility of a given NOx standard. With respect to NOx control, the emission control strategies noted below will be equally applicable to both non-catalyst and catalyst-equipped engines. In fact, greater calibration flexibility is provided with oxidation catalysts, because EGR or other calibration settings which may increase engine-out HC emissions are far less prone to increasing catalyst-out HC emissions. (Heavy-duty catalysts will be sized for CO control, and will contain a large reserve capacity for non-cold start HC oxidation.) Other HC and CO control techniques, notably air injection and cold-start management, will also have small effects on NOx emissions. For these reasons, all 1987 HDGEs will be discussed as a single group, as far as NOx control is concerned, for the remainder of this analysis.

For all engine families, the retarding of ignition timing will reduce NOx emissions. Retarded ignition timing decreases combustion temperatures (thereby decreasing NOx formation), and also increases post-combustion temperatures, post-combustion oxidation of HC and CO (presuming sufficient air injection), but can increase fuel consumption if sufficiently retarded.

Thus, the most likely strategy applicable to all 1987 HDGEs is the use of increased EGR. EGR reduces the maximum combustion temperatures in the engine cylinders, primarily by introducing a higher heat capacity fluid into the combustion process. (This fluid can then absorb more heat energy per unit temperature rise, thereby reducing maximum combustion temperatures.) EGR is extensively used in internal combustion engines, most notably current HDGEs. As noted above, current Federal HDGEs are calibrated to very low EGR flow rates, while in California--to meet a 1985 5.1 g/BHP-hr transient NOx standard--identical hardware but greater EGR flow rates will probably be necessary. The most likely change to current Federal HDGE EGR systems will simply be an increase in EGR flow rates.

At this time, there is ample evidence that achieving a 6.0 g/BHP-hr NOx standard for HDGEs by 1987 is easily feasible with modest hardware and calibration changes. This judgment was confirmed by Ford and GM in their comments to the January 19, 1981 ANPRM. Ford commented that ..."a [1986] NOx standard of about 6.0 g/BHP-hr may be achievable without experiencing unacceptable tradeoffs."* General Motors claimed that "a [1986] NOx standard of 7 g/BHP-hr may be feasible with no increase in fuel consumption".** GM also claimed that standards more stringent than 7 g/BHP-hr are feasible, but result in increased fuel consumption (see Figure 2-6). For example, a NOx standard of 5.1 g/BHP-hr was projected by GM to cause a two percent increase in fuel consumption.** Extrapolating from GM's submission, GM would expect about a one percent increase in fuel consumption to arise from a 6.0 standard. Ford's 1981 development work (Table 2-20), in which NOx levels well below 1987 target levels were readily achieved, further supports this judgment of feasibility. Again, there is ample evidence that a 6.0 g/BHP-hr NOx standard can be met by HDGEs with existing technology.

Furthermore, at the 6.0 g/BHP-hr level, it is not likely that the use of existing technology will measurably impact fleet-wide fuel economy, or preclude certification with other emission standards. The manufacturers' own predictions for 1986 indicated maximum fuel economy penalties of only zero to one percent. Their comments were based upon data collected in 1981, and could not include the substantial progress made by 1983 in reducing engine-out HC and CO emissions from HDGEs. Therefore, the manufacturers' 1981 assumptions with respect to the feasibility of a NOx standard at given levels of HC and CO, as indicated by the latest available data (Table 2-18), have proven to be overly pessimistic. In addition, the presence of a heavy-duty oxidation catalyst would more than eliminate HC tradeoff problems for the majority of engines in the very unlikely event that problems would be seen at a 6.0 NOx level. Finally, if the NOx/brake-specific fuel consumption (BSFC) tradeoff curves presented in Figures 2-1 and 2-2 are at all representative of current Federal HDGEs, which are now calibrated with minimal EGR, then large percentage reductions in NOx emissions should be possible with little or no negative fuel economoy effect. As presented in Table 2-19, only minor NOx reductions will in fact be required.

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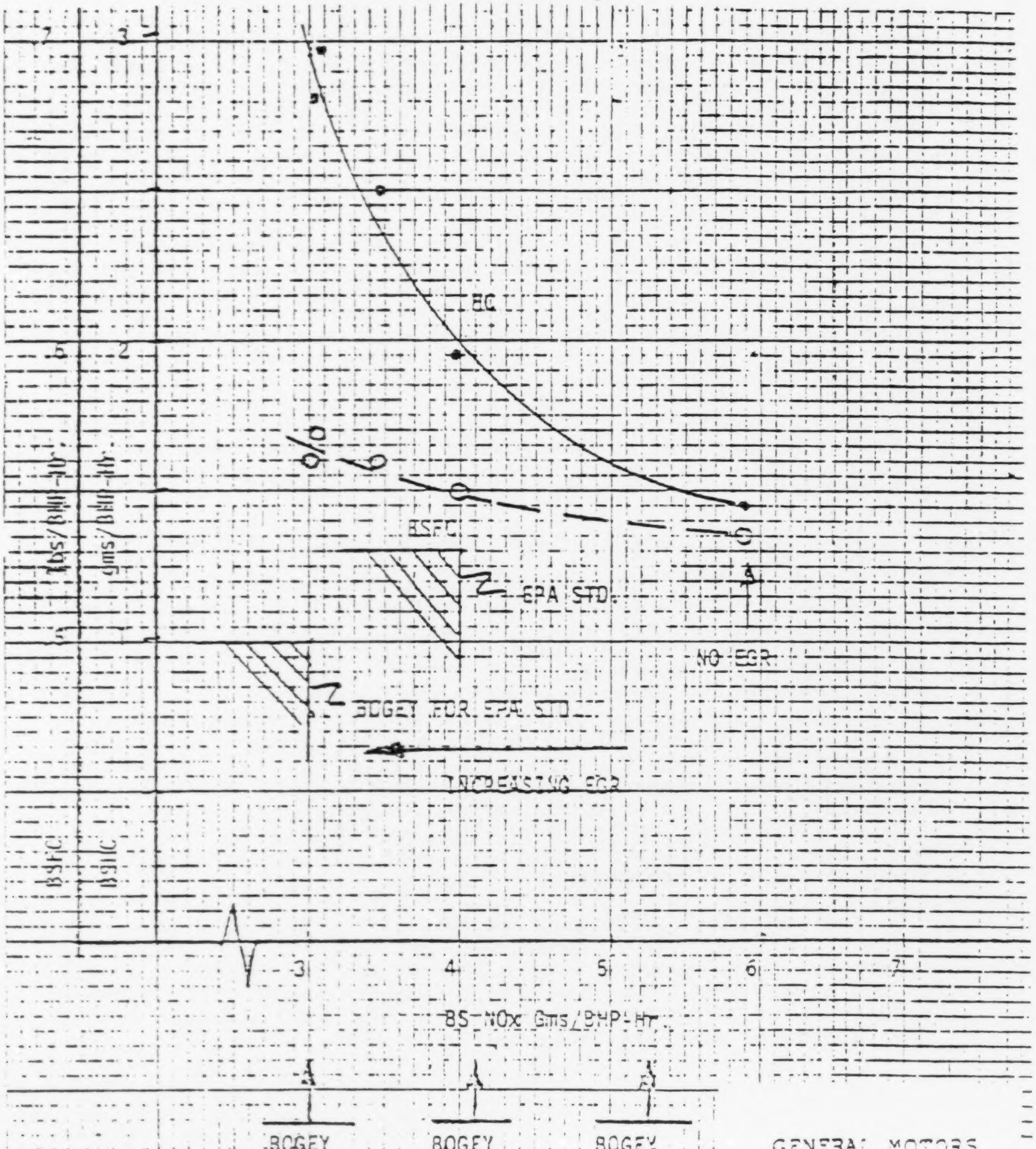
* Ford assumed half-life non-catalyst standards of 3.3 g/BHP-hr HC and 42 g/BHP-hr CO, no idle CO test, and an implementation date of 1986.

** GM assumed an HC standard no more stringent than 2.9 g/BHP-hr in 1986.

Figure 2-6

HDG Engine Emission/Economy Comparison
1984 350 V8 Prototype
Transient Test Cycle



GENERAL MOTORS
FE-2954
9/13/82

In summary, a 6.0 g/BHP-hr NOx standard for 1987 HDGEs is easily feasible. As noted in Table 2-19, a standard of 6.0 g/BHP-hr would require modest reductions (i.e., less than one-third) in about two-thirds of the 1985 prototype engine fleet; the other one-third of the engine fleet are already in compliance. EPA notes that compliance with a transient 5.1 g/BHP-hr NOx standard is required in California beginning in 1985, and that both future Federal and California engines will probably be equipped with identical EGR hardware but different calibrations. (Actual certfication data from 1985 California HDGEs will be available for review in the course of this rulemaking, at which time a precise quantification of tradeoffs can be made.) EPA also notes that Ford was readily able to achieve NOx emission levels well below the 1987 target level in their 1981 development work. Given the specific experience which will be gained with these heavy-duty engine families, given the decade of existing experience with NOx control in light-duty vehicles, given the relatively modest reductions necessary for a fraction of the fleet, and given the availability of well understood NOx control technologies for gasoline-fueled engines, a 1987 NOx standard of 6.0 g/BHP-hr is easily feasible for HDGEs within leadtime constraints, and should result in no fuel economy, performance, or driveability penalties.

C. Feasibility of a 1990 NOx Standard of 4.0 g/BHP-hr

A 4.0 g/BHP-hr NOx standard will not be stringent enough to require the adoption of three-way catalysts. This was not disputed by any manufacturer in comments to EPA's January 19, 1981 ANPRM, and will be readily apparent from the discussion which follows. Therefore, 1990 HDGE NOx control technologies should exhibit deterioration and production emissions variability similar to those of 1987. Therefore, using the earlier estimates for deterioration and production variability, a target level of 3.3 g/BHP-hr is derived as the low-mileage emission level needed to comply with a 4.0 g/BHP-hr NOx standard. (This is identical to Ford's projected target for a 4.0 NOx standard, as noted in Ford's comments to the ANPRM. GM, however, projected that a target of approximately 3.0 g/BHP-hr would be necessary.)

The emission reductions necessary to comply with a 4.0 g/BHP-hr standard are presented in Table 2-19. One 1985 prototype engine appears very close to the 3.3 g/BHP-hr level. On the other hand, the majority of engines would still require reductions of 21 to 57 percent to meet the 1990 standard (based upon prototype data available to EPA in 1983).

To achieve the required emission control, the simple techniques used in 1987 may not be sufficient in themselves to yield NOx levels approaching 3.3 g/BHP-hr in the majority of engines without the risk of significant penalties on engine performance and fuel consumption. There is evidence that non-catalyst HDGE NOx emissions can be further reduced by increased EGR. Most of the manufacturers' initial data, collected in 1981 in preliminary characterization projects,[19] indicate that HDGE engine-out NOx emissions in the 3-4 g/BHP-hr range can be achieved. In most cases, the achievement of these low NOx emission levels also resulted in adverse tradeoffs of fuel consumption, power, driveability, and other emissions. However, for example, Ford increased the exhaust system backpressure on a test engine as a quick and easy method of inducing increased EGR. While NOx emissions were reduced from 5.1 to 3.8 g/HP-hr, the increased backpressure decreased engine power and increased fuel consumption. As these observed adverse tradeoffs were largely attributable to the method by which EGR was induced and there are far less punitive methods of inducing EGR into production engines, these data cannot be used to quantify these effects.

However, as can be seen in Figure 2-2, too much EGR in any given engine can increase fuel consumption. Other manufacturers' test results also indicate that too much EGR can also increase other emissions, and impair driveability and maximum power. For example, some of GM's early test data are reproduced in Figure 2-3, in which NOx emissions in the 3.0 g/BHP-hr range were achieved, but with substantially increased HC. Thus, the preliminary test results submitted by the manufacturers in 1981 illustrate the limitations of simply increasing EGR rates and changing engine calibrations without performing compensatory engine development.

In their comments to the January 19, 1981 ANPRM (which proposed a 1986 NOx standard of 4.0 g/BHP-hr), Ford stated which technologies it believed held promise to reduce NOx emissions below 6.0 g/BHP-hr. These technologies included burn rate improvements, other combustion chamber revisions (including reductions in surface to volume ratio and compression ratio), camshaft revisions, friction reductions, EGR system improvements (including electronic controls and an EGR pump for high engine loads), thermactor air improvements, adoption of fuel injection, and adoption of electronically controlled high energy ignition. Ford argued that the interactive nature of these strategies, and also the need to maintain engine power and durability, necessitated detailed design and development programs with adequate time for dynamometer and vehicle demonstration. Ford concluded its comments with the following statement: "The leadtime to research, design, develop, and implement these advanced HDGE emission technologies is also an open issue, but it is Ford's judgment that production feasibility prior to the early 1990s is problematical and unlikely."

Ford's comments are consistent with experience; all of the above technologies indeed hold promise for HDGE NOx control. Before a judgment can be made, however, whether all or only a few would be required to allow compliance with 4.0 g/BHP-hr standard, the task of compliance needs to be more carefully examined, as does the emission control potential of the most widely adopted non-catalyst NOx control technology for gasoline-fueled engines--EGR.

The transient test for HDGEs is still relatively new. While NOx emissions are not at all as sensitive to the specific test cycle as other emissions,* there are variations in brake-specific emission rates between specific modes of the test cycle. For this reason, a thorough characterization (e.g., emissions "mapping") of engines is desirable, and perhaps essential if effective emission control strategies are to be developed for a given engine on a given test cycle.

To some extent, this has already been done for light-duty gasoline-fueled trucks, and also to a limited extent in current HDGEs. Many production EGR systems are controlled as a function of engine backpressure. As backpressure increases (i.e., the amount of combustion increases as measured by exhaust flow), the EGR rate is also increased to maintain EGR at a relatively constant percentage of total intake air. At wide-open throttle (as sensed by throttle position or manifold vacuum), the EGR is reduced; to some extent this may be desirable to maintain maximum power, but EGR is also not as necessary at WOT because the richer air/fuel ratios typically observed at WOT automatically reduce brake-specific NOx emission rates (see Figure 2-5). This type of EGR system is typically mechanically controlled, and is far removed in complexity and capability from the electronically controlled EGR systems present on current LDGVs, in which many other engine parameters (rpm, temperature, rate of change of load, etc.) can be used for precise mode-specific EGR control. As a first step, however, engines need to be carefully characterized to permit the optimization of emission control strategy, including the minimization of adverse tradeoffs.

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* See Chapter C of Reference 16.

It is not likely that the manufacturers' early test data on HDGE EGR, gathered in 1981, represented an elaborate matching of EGR systems to engines. They represented very quick characterization programs conducted on existing engines with little design optimization. Nevertheless, both the manufacturers' test data and other research (presented in Figure 2-1) indicate that increasing EGR decreases NOx. What remains is that adverse tradeoffs be minimized (i.e., that EGR systems be more carefully matched to an engines' operational requirements), and also that the engine be made more tolerant of increased EGR. One example of improved design to limit or eliminate these tradeoffs will be discussed below.

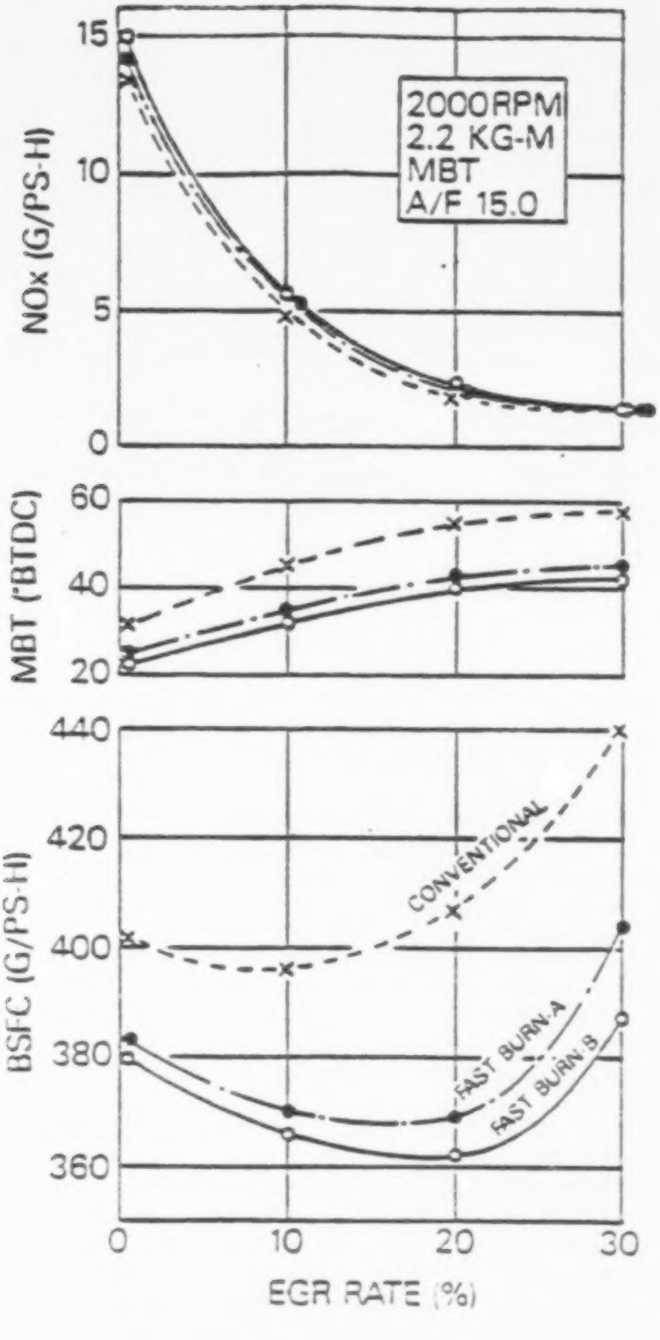
The tolerance of a spark-ignition engine for EGR can be dramatically increased by the use of "fast-burn" technology. Fast-burn technology involves modification of the combustion chamber to both increase turbulence and to reduce the distance the flame must travel through the combustion charge. Quite simply, the combustion event takes place in a shorter period of time than in other chambers. The use of this technology has been observed to improve engine thermal efficiency, EGR tolerance, and combustion stability with lower octane fuels.

This technique is already in limited production in LDV engines, one of the more well-known examples being the Nissan NAPS-Z engine. This engine uses...

> "...a swirl system for increasing the turbulence of the mixture in the cylinder and a two-point ignition system for shortening flame travel. Good driveability can be secured even with the quantities of EGR utilized by the adoption of fast-burn combustion... Thus, in the vehicles with the NAPS-Z engine, low NOx emissions and high fuel efficiency are achieved....In the fast-burn combustion engine, fuel efficiency improves as the quantity of EGR increases. The optimum point of fuel efficiency appears with an EGR of about 20 percent."[20]

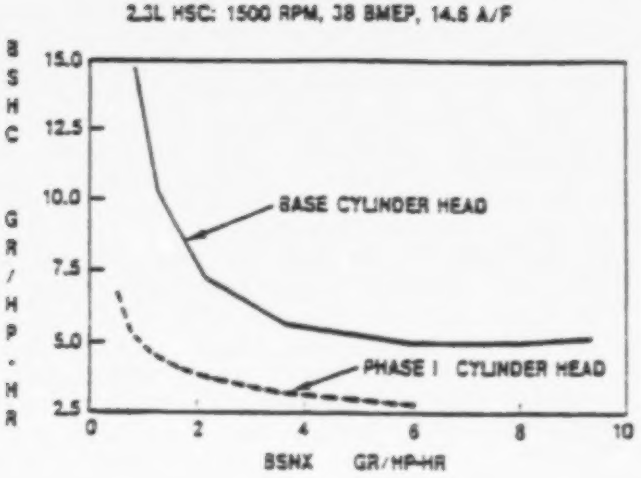
Figures 2-7 and 2-8 illustrate actual improvements in LDV engine performance using "fast-burn" techniques. In Figure 2-7, the EGR rate corresponding to minimum fuel consumption for the NAPS-Z engine was raised from 10 to 20 percent when fast-burn improvements were adopted; at the same time, brake specific NOx emissions were reduced by more than 50 percent. Similarly, Figure 2-8 presents performance data from the new Ford 2.3L High-Swirl-Combustion (HSC) engine also intended for use in LDVs. The "Phase I" (fast-burn) configuration produced more than a 66 percent NOx reduction from the "base" (non-fast-burn) configuration, while at the same time improving overall fuel efficiency and eliminating adverse tradeoffs with HC emissions. This performance is typical of the capabilities of fast-burn technology.

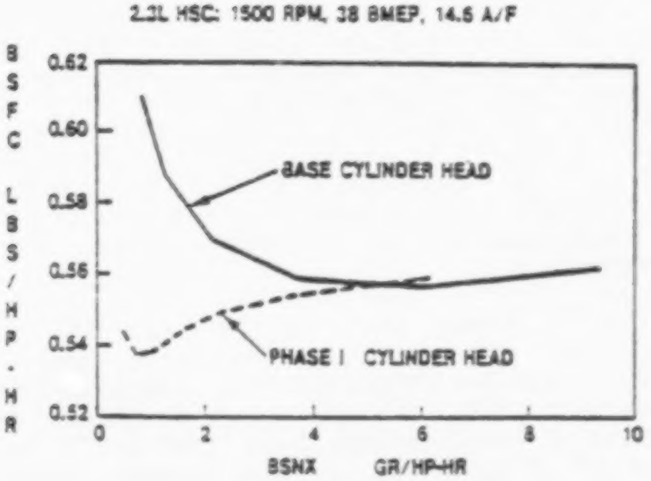
Figure 2-7



Comparison of NAP(s)-Z Engine Performance with Conventional and Fast-Burn Combustion Chamber (adapted from Reference 20.)

Figure 2-8





Comparison of Ford HSC Engine Performance with Conventional ("base) and Fast-Burn ("Phase I") combustion chamber (adapted from Reference 21)

This level of burn rate improvement, however, probably will not be necessary to allow compliance with a 4.0 standard. From current NOx levels, percentage reductions ranging from 3 to 57 percent, with an average of 39 percent, will be necessary (see Table 2-19). Again referring to Figure 2-1, to achieve NOx reductions of this size from levels where little EGR is already used requires average EGR rates of up to 10-15 percent for the highest emitting engines, and somewhat less than 10 percent for the "average" engine. Since modal requirements of the transient test and in-use operational requirements may dictate more mode-specific calibrations, both more and less EGR may be used at different modes. (For example, the rich air/fuel ratio calibrations at wide-open throttle produce less brake-specific NOx than other modes, and also are those modes when maximum available power is demanded. Less EGR may be used in these modes, to be compensated by more EGR at lighter loads.) Since sophisticated fast-burn technology can permit the use of 20 percent EGR while maintaining optimum engine efficiency (see Figure 2-7), the limits of NOx control for this technology probably will not be reached for a 4.0 standard. In fact, burn rate improvements, or any other NOx control technology, will probably be adopted to whatever extent is necessary to allow each individual engine family to comply with the standard. In the worst case, it is possible, given mode-specific calibrations and the highest emitting engines in Table 2-19, that substantial combustion chamber changes may be required on one or two engine families, and perhaps even electronically controlled EGR systems. For the most part, however, given the size of reductions which will be necessary for the majority of engines, only moderate burn rate improvements and other less sophisticated modification (see earlier page) should be necessary for most, assuming careful matching of EGR systems to engines. Even in the worst case, all of the technologies noted by Ford remain available for increased NOx control.

In summary, EPA agrees with Ford's list of potential NOx control technologies for HDGEs. However, most of these technologies should not be required for compliance with a 4.0 g/BHP-hr NOx standard. The degree of NOx reductions required from prototype levels (see Tables 2-19 and 2-20) are not very great (an average of 39 percent for the fleet), especially when compared to the potential reductions of 50 and 66 percent achievable with fast-burn technology. Burn rate improvements to combustion chambers, optimized EGR systems for mode-specific calibrations, and systematic optimization of the combination of air/fuel ratio, spark timing, and EGR rates to match the modal requirements of the transient test should be sufficiently effective to control NOx to a 4.0 standard.

As for leadtime, even the "maximum technology" approach discussed by Ford was speculated to be achievable by perhaps "the early 1990s"; the adoption and demonstration of the lesser and more likely level of technology should indeed be feasible for 1990. Unlike the heterogeneous fleet of HDDEs, HDGEs are technologically identical in almost all aspects except displacement. Their inherent similarity, both within their class and to other gasoline-fueled engines, makes the transfer of experience and technology possible. As was noted above, the types of technology required to meet a 4.0 standard have already appeared in production in LDVs. When compared to the almost revolutionary technological changes which HDDEs will undergo between 1987 and 1990, the technological difficulty associated with HDGEs meeting a 4.0 g/BHP-hr standard appears small.

Given the available development time, and given the availability and transferability of a variety of proven technologies, a 4.0 g/BHP-hr HDGE NOx standard will be feasible by 1990. Indeed, if HDGEs follow the same trend as LDVs with the implementation of burn rate improvements, then simultaneous reductions in NOx and fuel consumption would be expected. Only in the case of "quick-fix" development efforts, i.e., those in which little or no compensating engineering changes are made to HDGEs to improve EGR tolerance, would fuel economy or other penalties be observed on account of this standard.

While the 4.0 g/BHP-hr standard appears feasible via engine-related changes, it is possible that some manufacturers would apply three-way catalyst technology. Class IIb and III HDGEs will be equipped with oxidation catalyst in 1987 and their LDGT counterparts will likely be equipped with closed-loop, three-way catalyst technology. Thus, the step to three-way catalyst technology may be a natural one. While this would likely be more expensive with respect to its effect on initial vehicle cost, fuel economy and performance should improve. Overall, a manufacturer should only choose this option if three-way catalyst technology minimizes its total costs while meeting fuel economy and performance design goals.

D. Summary

The feasibility of two NOx standards for HDGEs was discussed: 6.0 g/BHP-hr in 1987 and 4.0 g/BHP-hr in 1990. The former appears feasible via increased use of EGR with no net effect on fleetwide fuel economy, performance, or driveability. The latter appears feasible via advanced combustion chamber modifications in addition to increased EGR rates. Again, no net adverse effects on engine operation are expected.

IV. Heavy-Duty Diesel Engines (HDDEs)

A. Introduction

There are a couple of factors which make a straightforward, quantitative assessment of the emission control capabilities of HDDEs difficult. First of all, many of the advanced technologies discussed here are currently in their infancy or have yet to be put in widespread production, which makes it difficult to quantify their effectiveness. Second, the technological heterogeneity of engines in the HDDE class makes it difficult to draw fleet-wide conclusions as to the viability of a given technology. These factors constrain one's ability to analytically address future emission control, and one's ability to confidently determine standards representing the most stringent control achievable without unacceptable cost. In short, unlike the earlier analysis for LDTs and HDGEs where specific production technologies and emission data were easily reviewed and conclusions drawn in a straightforward manner, this HDDE analysis must rely to a great extent on engineering judgment.

On the other hand, as will be reviewed in greater detail below, a large body of research is currently underway worldwide to characterize and improve the emissions performance of diesel engines. Equally important, market pressures are continually stimulating increased fuel economy in HDDEs. In many cases, the same technologies which improve fuel economy will also reduce HDDE emissions.

This analysis will begin with a review of the current NOx and particulate emission levels for HDDEs. It will then examine the technological feasibility and other impacts of HDDEs meeting two sets of proposed NOx and particulate standards: 1987 standards of 6.0 and 0.60 g/BHP-hr, respectively, and 1990 standards of 4.0 and 0.25 g/BHP-hr, respectively. The interaction between the control of these two pollutants requires that they be addressed together. The one exception is the discussion of trap technology for 1990, the trap having no effect on NOx emissions. Thus, the discussions of the 1990 NOx and particulate standards will be presented separately. Also, as indicated above, it should be noted that the outcome of this analysis with respect to the feasibility of NOx control determines the proposed NOx standards for HDGEs as well.

In addition, the analysis will examine the maximum feasible NOx and particulate levels achievable in 1990 and later years without the use of trap-oxidizer technology. The impact of these standards and control techniques on other important areas such as fuel consumption and HC emissions will also be addressed in each case.

B. Status of Current Technology

This portion of the analysis will examine the NOx and particulate emission levels of current HDDEs. In addition, it will also describe some of the characteristics of these engines which might explain their current NOx and particulate levels.

Table 2-21 is a summary of the HDDE NOx and particulate transient emission data currently available to EPA. The data comes from three sources: in-house EPA testing, testing conducted at the manufacturers' labs, and testing conducted as part of the EPA/EMA round robin program. When multiple tests on the same engine were available, the test results were averaged, except for tests conducted as part of the round robin program, where only those tests conducted at the engine's home lab were used.

The engines tested represent approximately 66 percent of all domestically produced HDDE sales. In most cases, the engines tested are actual production models. However, in a few cases the engines are viable production prototypes or production models with modified calibrations. While some caution should be used since every engine family sold in the U.S. is not represented, the engines in Table 2-21 adequately represent all HDDE technology.

The engines in Table 2-21 are grouped together in three subclasses, established based on their emission-related design and durability characteristics. The three subclasses are: 1) HDDEs of low horsepower and short useful life (which also happens to be those with indirect injection (IDI)), 2) direct injection (DI) HDDEs of moderate horsepower and useful life, and 3) DI HDDEs of high horsepower and long useful life. Since these three subclasses are roughly equivalent to the light, medium, and heavy HDDE subclasses established for useful-life purposes,[24] these common labels will be used here.

The NOx and particulate emission results shown in Table 2-21 are generally indicative of low mileage NOx and particulate emission levels of current engines. Thus, these levels represent a viable starting point for our assessment of the technological feasibility of future standards. The emission results from the one prechamber engine family are 3.01 and 0.46 g/BHP-hr NOx and particulate, respectively. (Only one other light HDDE is currently marketed, the IHC 6.9L diesel. While no transient emission data are currently available on this engine, its emissions are expected to be very near those

Table 2-21

Summary of NOx and PM Emission Results for Current HDDEs

Model	CID	Hp	Aspiration	Timing[1]	NOx	Part.	Source
Light HDDE: (all indirect injection)							
Detroit Diesel (DDA)							
V8-6.2	378		N[2]		3.01	.46	EPA
Medium HDDE: (all direct injection)							
Caterpillar (CAT)							
3208DIT	636	250	T	16.00	10.00	.59	M
3208DINA	636	210	N	16.00	8.49	.63	RR
3208DINA	636	200	N/EGR	16.00	4.30	.88	M
3208DINA	636	200	N/EGR	16.00	4.13	1.09	M
Cummins							
NH250	855	225	N	.029	8.11	.72	SwRI
NH250	855	225	N	.029	6.80	.83	M
Detroit Diesel (DDA)							
8.2T	500	200	T	4.00	5.99	.43	M
8.2T	500	200	T	6.00	6.80	.43	M
8.2T	500	205	T	6.00	6.88	.44	M
8.2T	500	200	T/EGR	4.00	5.04	.67	M
8.2T	500	200	T/EGR	6.00	5.60	.69	M
8.2T	500	200	T/EGR	3.00	4.17	1.06	M
8.2T	500	200	T/EGR	6.00	4.73	1.42	M
International Harvester (IH)							
DTI466B	466	210	TA	--	4.05	.81	RR
DTI466C	466	210	TA	17.00	4.64	.62	M
DTI466C	466	210	TA	17.00	4.62	.62	M[3]
DTI466C	466	210	TA	20.00	5.50	.57	M[3]
DTI466C	466	210	TA	23.00	6.95	.57	M[3]
DT466C	466	210	T	20.00	5.50	.56	M[3]
DT466C	466	210	T	23.00	7.05	.53	M[3]
DT466C	466	210	T	26.00	9.65	.43	M[3]

[1] Degrees before top dead center, except Cummins, which is in inches.

[2] N = Naturally aspirated
T = Turbo charged
TA = Turbocharged and after
EGR = Exhaust gas recirculation

[3] Hot start only.

[EPA] U.S. EPA.

[M] Manufacturers tests.

[SwRI] Southwest Research Institute.

[RR] EPA/EMA Roundrobin Test Program.

Table 2-21 (cont'd)

Summary of NOx and PM Emission Results for Current HDDEs

Model	CID	Hp	Aspiration	Timing[1]	NOx	Part.	Source
Heavy HDDE (all direct injection)							
Caterpillar (CAT)							
3306DITA	638	270	TA[2]	18.00	9.02	.73	M
3406DITA	893	377	TA	19.50	4.78	.81	RR
3406DITA	893	310	TA	22.00	8.20	.58	M
Cummins							
NTCC240	855	240	T	.063	4.78	.77	M
NTC350	855	350	TA	--	9.00	.70	M
NTC350	855	350	TA	.065	7.23	.58	M
NTCC400	855	400	TA	.062	5.31	.85	M
VTB903	903	275	T	.101	5.27	.72	RR
Detroit Diesel (DDA)							
6V92TA	552	335	TA	7.00	4.92	.83	M
6V92TA	552	335	TA	7.00	4.59	.83	M
8V71N	568	262	N	14.00	6.31	.69	SwRI
8V71TA	568	350	TA	14.00	7.03	.42	RR
8V92TA	736	435	TA	7.00	8.68	.46	M
8V92TA	736	435	TA	10.00	9.53	.41	M
8V92TA	736	435	TA	12.00	11.65	.34	M
8V92TA	736	335	TA	7.00	5.61	.52	M
8V92TAS	736	335	TA	14.00	9.24	.44	M
Mack							
EC6-235	672	235	T	20.00	9.73	.81	M
EM6-250	672	250	TA	23.00	9.11	.40	M
EM6-250R[3]	672	250	TA	24.00	8.81	.49	M
EM6-285	672	285	TA	22.00	6.97	.61	RR
EM6-300	672	300	T	24.00	8.20	.55	M
EM6-300R[3]	672	300	TA	23.00	7.98	.55	M
E6-350[3]	672	350	TA	23.00	8.61	.36	M

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[1] Degrees before top dead center, except Cummins, which is in inches.

[2] N = Naturally aspirated
T = Turbo charged
TA = Turbocharged and after
EGR = Exhaust gas recirculation

[3] "R" refers to reduced rated engine speed.

[EPA] U.S. EPA.

[M] Manufacturers tests.

[SwRI] Southwest Research Institute.

[RR] EPA/EMA Roundrobin Test Program.

of the 6.2L GM engine.) The medium HDDEs range in NOx from 4.05 to 10 g/BHP-hr and range in particulate from 0.43-1.09 g/BHP-hr. Similarly, the heavy HDDEs range in NOx from 4.78 to 11.65 and in particulate from 0.34 to 0.85 g/BHP-hr.

Beginning in the 1984 model year, the state of California implemented optional transient test based emission standards for HDEs. Included in this change was a NOx standard of 5.1 g/BHP-hr. All five domestic manufacturers have certified at least one engine family under this option and their certification levels (full-life) are shown in Table 2-22. There is no California particulate standard, so the particulate emission levels of these engines are not available, except insofar as the California designs of Table 2-22 are represented by engines shown in Table 2-21, which can be deduced from similar NOx levels.

Before going on to a discussion of conventional and advanced NOx and particulate emission control approaches one final point needs to be made. Even though the HDDEs shown in Tables 2-21 and 2-22 are representrative of current engines, the manufacturers' HDDE product offerings are constantly changing and evolving. This is being driven primarily by durability and fuel economy concerns in the marketplace. Therefore, it is expected that some of the engines shown in Table 2-21 will not be produced in the future. Those engines which are less fuel efficient or do not have the durability demanded by the marketplace will be replaced by engines which are more fuel efficient, durable and which are designed for inherently lower emissions. The HDDEs in Table 2-21 represent only current technology engines, not future technical capabilities. Even absent more stringent emission standards there would be a trend to more efficient engines. The application of turbocharging, aftercooling and electronic engine controls will all increase, bringing with them improved emission control as well.

The next three sections of this analysis turn to discussions of the technical feasibility of the proposed NOx and particulate standards for 1987 and 1990. In the last section, feasible 1990 non-trap particulate levels are also examined.

C. Technological Feasibility of the Proposed 1987 NOx and PM Standards

The discussion of the feasibility of the proposed 1987 NOx and particulate standards falls into three sections. The first section estimates design target levels associated with the proposed standards. This is necessary because the emissions

Table 2-22

1984 Model Year HDDE
California NOx Certification Levels--Transient Test

Manufacturer	Model	CID	Aspiration	Deteriorated NOx Level*
Catepillar	3406T	893	T	5.02
	3208T	636	T	4.5
	3208E	636	NA	5.0
Cummins	903I	855	T	4.7
Mack	10	672	T	4.3
	12	672	T	4.6
Inter. Harvester	DT-466	466	T	4.8
	DTI-466	466	TA	4.5
	9.0L	551	NA	4.8
General Motors	8.2T	500	T	4.7
	8.2	500	NA	5.0
	6V-92TA	552	T	4.7

---

* Multiplicative DFs used, g/BHP-hr.

data in Table 2-21 are low-mileage levels and cannot be directly compared to a standard. The second section contains the bulk of the technical feasibility analysis. There the analysis first addresses IDI engines and then DI engines. The final section addresses the impact of the proposed standards on HC emissions and fuel consumption.

1. Establishment of Design Target Levels

The equation for determining the design target level (TL) is:

$$TL = \frac{MPL-DF}{AQL}$$

Where:

MPL, DF, and AQL are as defined above.

One difference between the design target equation for HDDEs and that for LDTs is that the DF is expressed as an additive factor and not as a multiplier, due to the absence of an aftertreatment device in the exhaust.

As the technology feasibility analysis which follows is not able to have the precisions of those for LDTs and HDGEs, it is not necessary to precisely determine the TL. In fact, as the various inputs to the above equation do vary from engine to engine, the ranges indicated below may be more indicative of actual TLs than a single-point estimate. In addition, the process of establishing TLs is intended here to simulate how manufacturers take into account engine variability and deteriorations. However, for any given engine, a manfacturer may choose to reduce deterioration variability or the confidence in passing an audit rather than reduce emissions to the "standard" target level described here. Thus, it may not be necessary to reduce emissions to the degree shown here.

For a NOx standard of 6.0 g/BHP-hr, the MPL would be 6.0499 g/BHP-hr or essentially 6.05 g/BHP-hr. For a particulate standard of 0.6 g/BHP-hr, the MPL would be 0.605 g/BHP-hr.

The equation used to compute the AQL factor has been developed in past analyses and is:[18]

$$AQL = [(1 + z_{.1} \times \frac{CV}{1.732} + (z_{.4} \times CV)]^{*}$$

Where:

z = value of the z statistic for alpha (one-sided) = 0.1 (1.28) and alpha = 0.4 (0.25)

CV = within-lab coefficient of variation between engines for emissions of a given pollutant

The CV for NOx will be assumed to be approximately 10 percent. This is supported by comments made by Cummins and the results of the EPA/EMA HDDE round-robin test program, which showed an average within-lab CV of 4 percent for a single engine.[22,23] Using the above equation, the AQL factor is 1.1. for NOx.

The CV for particulate was estimated to be 10 percent by Cummins, and to be roughly the same as that for HC by Caterpillar, which is 16 to 20 percent. As the EPA/EMA round-robin testing indicates that variability for particulate should be somewhat below that for HC,[23] a range of 10 to 15 percent will be used here, yielding an AQL factor of 1.1-1.15 for particulate.

The next step is the determination of the full-life deterioration factors. As there is a relationship between the full-life period and the durability characteristics of an engine (i.e., long-lived engines are designed more durably and their emissions increase more slowly), engines with different full-life periods tend to have similar DFs. Thus, DFs will be estimated for all HDDEs as a single class here.

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* The "z" statistic is preferred here over the "t" statistic since the standard deviation of the population can be accurately estimated based on past experience. Also, 1.732 is the square root of 3, the number of prototype engines assumed to be developed.

A review of the 1983 HDDE certification results shows that more than one-third of the families had zero DFs, with the overall mean and median DFs being 0.24 and 0.20 g/BHP-hr, respectively. Since these values are roughly half life DFs, mean and median full-life DFs would be approximately 0.48 and 0.40 g/BHP-hr, respectively. Given the frequency of a zero DF and the lack of historical pressure to control NOx, it will be assumed that the higher DFs can be reduced to the current mean DF. This results in an overall range of 0-0.48 g/BHP-hr for the NOx DF.

No actual particulate durability data are available, however, it is reasonable to expect that particulate should deteriorate no more than NOx or HC on a percentage basis. Most HDDEs certified in 1983 have half-life HC DFs equal to five percent or less of the low mileage level, and doubling this would lead to a full-life DF of approximately 10 percent. As a NOx DF of 0.48 g/BHP-hr is equivalent to about six percent, a range of 6-10 percent, or 0.04-0.06 g/BHP-hr at the 0.6 g/BHP-hr level, will be used here.

Substituting these figures into the expression for the target level given above, the design target level for a 6.0 g/BHP-hr NOx standard is 5.1-5.5 g/BHP-hr. The particulate target level is estimated to be 0.47-0.51 g/BHP-hr.

2. Technological Feasibility by HDDE Subclass

As indicated above, HDDEs can be divided into three subclasses: light, medium, and heavy. While the basic combustion technology of current light HDDEs is distinct (i.e., use of prechamber, or indirect injection (IDI) technology), that of the medium and heavy HDDEs is more similar. All medium and heavy HDDEs use direct injection (DI) designs. Furthermore, most medium HDDEs are naturally aspirated (roughly 60 percent), while nearly all heavy HDDEs are turbocharged and aftercooled (roughly 90 percent). However, some medium HDDEs are both turbocharged and aftercooled (2-3 percent). As the techniques available to both medium and heavy HDDEs to reduce emissions are very similar, they will be treated together below as DI engines.

a. IDI HDDEs

Two IDI HDDEs are currently produced: a 6.2L engine produced by Detroit Diesel (DDA) and a 6.9L engine produced by International Harvester (IH). The DDA engine is also currently used in LDTs.

EPA currently has full transient emission data only on the DDA engine (see Table 2-21). As can be seen, the 6.2L engine currently emits 3.01 g/BHP-hr NOx and 0.46 g/BHP-hr particulate, both of which are well below the target emission levels of 5.1-5.5 g/BHP-hr NOx and 0.47-0.51 g/BHP-hr particulate. No transient emission data is available on the IH 6.9L engine. However, the 1983 13-mode NOx certification level of 4.25 g/BHP-hr indicates that the 6.9L can also meet the NOx target level in its current configuration, as transient and 13-mode NOx emissions agree fairly well.

Any additional light HDDEs introduced prior to 1987 should also be able to comply with both standards, due primarily to the inherently lower emissions of IDI engines. It is possible that DI engines could be introduced into the light HDDV class at some future date. If that occurred, their emissions should be similar to those of current medium HDDEs, and the control of their emissions would be similar to that described below.

b. DI HDDEs

Two factors make the discussion of emission control more difficult for DI engines than for IDI engines. One, DI engines tend to have inherently higher NOx and particulate emissions than IDI engines and more control is needed. Switching to IDI technology is not feasible due to the fuel economy penalty involved (10-15 percent). Two, a wide variety of DI engines exist. Some are naturally aspirated, some are turbocharged, and some are turbocharged and aftercooled. Also, the combustion chamber and fuel injection technology of each manufacturer tends to be somewhat unique, each having its relative advantages and disadvantages. Thus, what reduces emissions on one engine may not be applicable to another. On the other hand, some techniques are transferable.

To aid in this examination, the following discussion will be divided into three parts. The first part will address non-emission related engine changes expected in the 1987 timeframe that will also lower NOx and particulate. These are mainly improvements to brake specific fuel consumption (BSFC). The second part will address NOx control technology. The last part will address particulate control. Where data are available, they will be referenced. However, in many cases, data are not yet available or the data are still proprietary; therefore, engineering judgment has to be relied upon.

i. BSFC Improvements

Reductions in BSFC reduce brake-specific emissions proportionately because emissions tend to remain constant on a fuel-specific basis. Lower BSFC means less fuel burned and thus, lower absolute emissions. However, the work generated over the cycle (BHP-hr) remains constant and brake-specific emissions (g/BHP-hr) decrease.

The BSFC of DI engines is expected to improve steadily over the foreseeable future due to the high mileage of the vehicles they power and the constant pressure to cut operating costs. One analyst's recent estimates of BSFC improvements over the 1982-87 timeframe for medium and heavy HDDEs are shown in Table 2-23.[24] As can be seen, overall improvements of 7-8 percent are expected. Also, DDA recently published a history of recent BSFC improvements on their 6V-92TA showing a 14 percent improvement from 1976 to date and an additional 4-6 percent in the near future.[25] While it is not possible to independently confirm the projections contained in Table 2-23, the GM experience and the fact that every major HDDE manufacturer is known to have programs in place to improve engine efficiency, argues for lower BSFCs in the future.

The result of this projection is that the emission data of Tables 2-21 and 2-22, which represent pre-1983 technology, should be reduced by some amount (e.g., 5-10 percent) prior to the addition of specific emission controls. This will be discussed further in the next two sections.

ii. NOx Control

The most common approach currently used to reduce NOx emissions is static fuel injection retard. It is simple and inexpensive to implement and its effect on NOx emissions can be easily characterized. Those DI engines of Tables 2-21 and 2-22, which meet the NOx target level of 5.1-5.5 g/BHP-hr, do so for the most part with injection retard. These engines comprise a representative sample of DI HDDEs, as three of the engines are naturally aspirated, three are turbocharged and six are turbocharged and aftercooled, and roughly half are medium HDDEs and half heavy HDDES. Thus, there is little doubt that all DI engines can meet these levels by simply applying injection retard. And because of its low cost--it is essentially an engine adjustment--, it receives the most attention when NOx controls are discussed. The drawback with this approach to NOx control is that large amounts of injection retard can increase particulate emissions and BSFC. The effect of timing retard on particulate is indicated by the data in Table 2-21.

Other techniques are available to reduce NOx emissions without the particulate and BSFC tradeoffs, such as aftercooling turbocharged engines. Because of the short

Table 2-23

Projected Improvements to HDDE Efficiency (%)*[24]

Source of Improvement	Light HDDE		Medium HDDE		Heavy HDDE	
	1982-87	1987-92	1982-87	1987-92	1982-87	1987-92
General Improvements	2	3	2	3	5	5
Direct Injection	2	5	--	--	--	--
Turbocharging	--	2	2	1	--	--
RPM Reduction	--	2	1.8	1.4	0.9	--
Lubricants	1	1	1	1	1	1
Aftercooling	--	--	0.5	1	--	--
2 to 4 Stroke	--	--	--	--	--	0.7
Turbocompound	--	--	--	--	--	1.5
Reduced HP	--	--	--	--	0.3	0.5
	5%	13%	7.3%	7.4%	7.2%	8.7%

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* Fleetwide averages for new engines.

leadtime available these techniques are unlikely to be applied to many HDDEs in the 1987 timeframe unless already planned.* Overall, because of its low cost and easy application, timing retard appears to be the most likely approach to meeting a 6.0 g/BHP-hr NOx standard.

There are two ways one can examine the effect of timing retard on particulate emissions. (The effect of timing retard on BSFC will be examined below in Section 3.b.) The data in Tables 2-21 and 2-22 can be used in both cases.

One approach is to measure the increase in particulate emissions on a given engine per unit decrease in NOx emissions. Restricting the analysis to situations where at least three timing settings were examined and all of the data were taken at the same laboratory, one sees that particulate increases by 0.02-0.04 g/BHP-hr per 1.0 g/BHP-hr reduction in NOx (or from a slightly different angle, particulate increases 0.26-1.38 percent for each 1.0 percent reduction in NOx).

The other approach is to examine absolute particulate levels at NOx levels within 5-10 percent of the NOx target levels, which have been achieved via timing retard. For example, at these low NOx levels, both the DDA and IH medium HDDEs are still very near the particulate target, as is the DDA 8V-92TA (335 hp). On the other hand, other engines (e.g., Cummins NTCC400 and Mack EC6-235) appear to require up to 50 percent reductions in particulate levels at those NOx levels. Thus, the degree of particulate control required at NOx levels of 5.1-5.5 g/BHP-hr varies significantly among engines.

iii. Particulate Control

To date, no particulate standards have been applied to HDDEs. Thus, while HDDE manufacturers have some experience related to controlling diesel smoke, they have never been required to seriously address the control of particulate emissions from each of their engines. This is particularly true of particulate formed during transient engine operation, since the focus on transient emissions only began with the development of the EPA transient engine cycles in the late 1970's; the exception again being the modest control of smoke under three specific transient conditions. Thus, one would expect that some reduction in the current level of diesel particulate could be achieved with relative ease via the standard application of the techniques which have already led to low particulate emissions on some current engines. However, due to the heterogeneity of DI HDDEs, it would be inappropriate to assume that the straightforward transfer of these techniques could reduce the particulate levels of all engines to those of the lowest emitting engines of Table 2-21. At the same time, such levels should be approachable within subclasses of DI HDDEs (i.e., naturally aspirated, turbocharged, and turbocharged and aftercooled engines). As described at the close of the previous section, there are examples of turbocharged and turbocharged/aftercooled engines which are currently at or near both the NOx and particulate design target levels. Naturally aspirated engines may have a more difficult time as none currently approach the two design target levels simultaneously.

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* Variable injection timing via mechanical or electronic controls can reduce NOx with reduced tradeoffs and may be able to be introduced by 1987. However, it will be discussed as a particulate control technique below.

In addition to incorporating current design features shown to produce low particulate levels, there are several, more generic approaches which can be used to reduce particulate emission levels in the 1987 timeframe without increasing NOx emission levels. The approaches include fuel injection system modifications, combustion chamber modifications, transient air-fuel ratio control, and variable injection timing. Fuel injection system modifications primarily include increased fuel injection pressure and changes in the fuel injection nozzle design. Turbocharging, while promising particulate reductions, is probably not available for widespread application for 1987 due to leadtime constraints, unless already planned for other reasons by the manufacturer.

Increased fuel injection pressure has been demonstrated in a past EPA program to decrease particulate emission levels by 50 percent on a Mack engine [25a] and in the results of manufacturer experimental programs reported to EPA. However, high-pressure injection also appears to increase NOx emissions. The higher injection pressure increases the fuel injection rate and speeds up the combustion process, much like injection timing advance. After retarding timing to account for this, a net particulate decrease should result. While increasing injection pressure is a substantial modification to the engine considering the leadtime available, for 1987, a number of manufacturers are known to have programs in place to modestly increase fuel injection pressure (20-30 percent). These modest increases could be expected to provide net particulate reductions on the order of 5-10 percent for those manufacturers already planning to do so. It also appears that increased fuel injection pressure reduces BSFC, providing another incentive for its implementation.

Modifications to the fuel injection nozzle include zero sac nozzle volumes to reduce fuel dribble at the end of injection, damped nozzle checks to prevent secondary injection, and optimized spray nozzle angle, including the number of spray holes, and size of holes. In addition to having potential to reduce carbonaceous particulate, these modifications have been shown to be effective in the past in controlling HC emissions,[16,18] which affects particulate as well by reducing the amount of soluble organics absorbed. The degree of control achievable will vary from engine to engine and cannot be precisely quantified here. However, HDDE manufacturers, such as Caterpillar, have identified such areas for improvement and expect measurable particulate reductions.[25c]

Combustion chamber modifications include changes in piston and ring design to reduce dead volume within the combustion chamber, as well as air inlet port redesign to affect the rate of swirl and in turn improve air-fuel mixing. Reducing oil flow past the piston rings can also reduce particulate emissions, as it has been shown that a portion of the particulate emitted comes from the oil. For naturally aspirated engines, the amount of air available in the cylinder can be increased by adding an additional intake and exhaust valve per cylinder (a 4-valve engine). Again, the net effect on particulate emissions is difficult to quantify due to differences between engines.

Preventing overfueling throughout all engine operating conditions, specifically the prevention of overly low air-fuel ratios typically occurring during transient engine operation (e.g., during an acceleration) and more flexible control of injection timing, probably hold the most promise of any of the techniques discussed thus far for the 1987 timeframe. This potential is related to the fact that the engine designs represented in Tables 2-21 and 2-22 include no improvements related to optimizing particulate and NOx emissions. By examining instantaneous NOx and particulate emissions over the transient cycle, periods of high emissions can be identified and addressed. Particularly, the allowable fuel rate can be limited and timing adjusted. While full optimization of these parameters will not occur until the advent of electronics (which will be discussed below), partial control can be achieved via mechanical means.

An estimate of the potential for particulate reduction via better transient air-fuel ratio control can be obtained from the difference between 13-mode and transient emissions, since the former includes no transient effects and the latter does. This difference ranges between 0.1 and 0.3 g/BHP-hr on current engines. Most of this difference should be controllable via improved control of fuel governing so that transient emissions will eventually match steady-state emissions. By 1987, a portion of this difference should be controllable by the use of improved mechanical fuel governors.

An indication of the potential for variable injection timing can be obtained from analyzing 13-mode NOx and particulate emissions. In general, NOx emissions on a brake-specific basis are relatively constant from mode to mode, while particulate emissions are heavily weghted toward the four high-power modes (Nos. 5, 6, 8, and 9). This indicates an ability to retard timing at light loads to reduce NOx without commensurately increasing particulate emissions. As roughly half of the transient cycle occurs at such light loads, one could surmise that roughly half of the 2-4 g/BHP-hr reductions in NOx emissions occurring via static timing retard in Table 2-21 may be achievable with little increase in particulate. As particulate emissions otherwise increased 0.05-0.6 g/BHP-hr, this potential could be quite large.

Mechanical timing controls were described in manufacturers' comments to the rulemaking. Timing is controlled by changing the position of a cam follower roller on the camshaft which is actuated by an air actuator cylinder. The air cylinder piston motion is based on fuel rail pressure.

Although the widespread use of electronic engine controls (EECs) is not expected until later in the decade, some limited application of EECs is expected prior to 1987. For example, DDA is using electronic control of injection timing, bypass ratio, and fuel governing on a prototype methanol-fueled HDDE currently operating in a transit bus in California.[25b] DDA plans to introduce EEC technology in 1985, so at least some models will have access to this technology by 1987. While it is expected that HDDEs should be able to comply with the 0.6 g/BHP-hr particulate standard without electronics, electronics should be available for those models experiencing difficulty.

To place the need for the modifications discussed above in some context, the medium HDDEs of Table 2-21 will be examined in some detail. Overall, the modest emission reductions needed by the DDA and IH engines should be easily achievable by any number of the above techniques. The Cat 3208, which Caterpillar is known to desire to keep in the market as a naturally aspirated engine, will require most of the above-mentioned techniques related to the combustion chamber and fuel injection system. Caterpillar is known to be actively working on techniques like these for this engine.

Caterpillar has indicated the types of improvements they expect to make to their engines and these are shown in Table 2-24.[25c] Caterpillar was the most optimistic of all the HDDE manufacturers about complying with the particulate and NOx standards of 0.6 and 6.0 g/BHP-hr, respectively, in the near term, and went so far as to recommend these levels as feasible standards for 1986. While it is known that Caterpillar has found the task somewhat more difficult than it believed at that time, Caterpillar is still targeting their efforts toward these levels and expects to reach them.[25c] Thus, while the Cat 3208 may require many of the above-mentioned techniques, it is expected to be able to comply with the 1987 standards.

The degrees of modification required by heavy HDDEs fall into similar categories; some, like the DDA and IHC medium HDDEs, require little modification, while others, probably the majority, require greater modification like that described for the Caterpillar engine. In addition, several manufacturers, including Mack, [22] have indicated that in the short term, production of one or more models may have to be dropped. However, it would not be appropriate to attribute this solely to the emission standards. While more stringent emission standards do tend to force aside lagging technology, it is also clear that HDDE models which manufacturers decide to drop are also likely to be deficient in other aspects such as durability, fuel economy, and market penetration, and that manufacturers have decided that the investment required to meet the standards is not justified by the potential payback in retaining the model in its product line. A number of HDDE models are over 20 years old and currently have very low sales (e.g., below 1,000 engines). The equipment to produce these engines has been fully depreciated long ago, justifying continued production despite low sales. These NOx and particulate emission standards represent the first major requirement for new investment on these models to come along in some time. Overall, the lost sales from these engines should be made up elsewhere in the manufacturer's product line.

3. Other Impacts of the Proposed 1987 NOx and Particulate Standards

a. Hydrocarbon Emission Levels

It is generally recognized that injection retard tends to increase HC emission levels. However, techniques which are effective in controlling particulate emissions tend to reduce HC emissions. Given that a net decrease in particulate emissions will occur, we expect no net increase in HC levels should occur.

Table 2-24

Modifications Being Made to Caterpillar Development Engines [24]

- Improved Fuel System
  - Higher Injection Pressures
  - Faster Injection Rates
  - Damped Checks to Eliminate Secondary Injection
- Lower Sac Volume Fuel Nozzles
- Reduced Crevice Volumes
- Improved Turbocharger Efficiency
- Improved Charge Air Cooling

b. Fuel Economy

There is a well established, adverse tradeoff between NOx emission control via retarded injection timing and fuel consumption. However, no fuel consumption increase is expected for IDI engines since their IDI technology provides compliance with the proposed NOx standard without significant timing retard. The potential fuel consumption effect for DI HDDEs is discussed below.

In their previous comments on the fuel economy impact of further HDDE NOx control, several manufacturers provided estimates of the fuel consumption impact of NOx standards of approximately 6.0 g/BHP-hr.[22] Mack, Cummins, and Caterpillar estimated fuel consumption penalties of 2-11 percent for NOx standards of 5-6 g/BHP-hr.

In a follow-up presentation to EPA in October 1983, Caterpillar estimated that, with NOx and particulate standards of 6.0 g/BHP-hr and 0.60 g/BHP-hr respectively (those levels recommended by Caterpillar in the hearing on the initial proposal of the particulate standard), fuel consumption penalties at or near the lower end of the above range were likely.[25c] This is based largely on the results of their newly released 3406B model which employs many of the emission control techniques discussed above (California comparisons).

In their 1981 report on NOx control from HDEs,[25d] the National Academy of Sciences (NAS) estimated fuel consumption penalties of 2.5 to 4 percent for a 6 g/BHP-hr target level and 7 to 12 percent for a 4 g/BHP-hr target level. By simple interpolation using a NOx target level of 5.2, the NAS projections provide fuel consumption penalty estimates of about 4 to 7 percent (the NAS projection was based on 13-mode relationships and covered only DI HDDEs; IDI HDDEs were not available when the NAS study was conducted).

Except for the latest Caterpillar estimate, the above estimates of fuel penalty do not take into account the particulate control techniques which will be used to comply with the 0.6 g/BHP-hr standard. Thus, they likely overestimate the effect of the 6.0 g/BHP-hr NOx standard.

Given this information, a fuel consumption increase of at most two percent is projected for medium and heavy HDDEs. If timing retard were the only NOx control technique used, the full two percent penalty would be expected. The use of other techniques, such as advanced charge air cooling, electronics etc., should all reduce this effect, to the extent they are applied prior to 1990. The application of this advanced NOx technology in 1990 (which is discussed below with respect to the 1990 standards) should eliminate this 1987 impact. Thus, any impact of the 1987 standards should be temporary and not long lasting.

D. Feasibility of the Proposed 1990 NOx Standards

1. Establishment of Design Target Level

As was discussed previously, determination of the target level requires estimation of the MPL, the AOL factor, and full-life DF. For a 4.0 g/BHP-hr NOx standard, the MPL is 4.05 g/BHP-hr.

Estimating the AOL factor and the full-life DF is more complicated since they can vary somewhat with the technology used to comply with the emission standard. As will be discussed below, it is expected that compliance with a 4.0 g/BHP-hr NOx standard (beginning from a 6.0 g/BHP-hr level) will require application of various combinations of electronic engine controls (EECs), advanced charge air cooling, and possibly in some cases some additional injection timing retard and exhaust gas recirculation (EGR).

For the 6.0 g/BHP-hr NOx standard, the AOL factor was determined to be 1.1 and the full-life DF was 0-0.48 g/BHP-hr. The net effect of adding the predominant technologies mentioned above (i.e., electronics, EGR, and improved charge air cooling) is difficult to ascertain due to a complete absence of data. Electronic controls should decrease variability and deterioration. Improved charge air cooling should have no effect on variability or deterioration. However, EGR (if used) may increase variability and deterioration, since the EGR rate may vary between engines and with time. While there is some indication that variability and deterioration may decrease overall, the effect cannot be quantified. Thus, it will be assumed that the AOL factor and DF will remain constant at 1.1 and 0-0.48 g/BHP-hr, respectively, with a 4.0 g/BHP-hr standard. Using these factors yields a NOx target level of 3.2-3.6 g/BHP-hr.

2. Technological Feasibility by HDDE Subclass

This section will follow the same general outline as that above for the 1987 HDDE standards. IDI HDDEs will be addressed first, followed by DI HDDEs. The DI HDDE discussion will be divided into two sections, BSFC improvements and NOx controls. Following all of this will be a discussion of the effect of NOx control on HC emissions and BSFC.

a. IDI HDDEs

As was discussed above, there are currently only two IDI HDDE models. Engines with IDI technology generally have very low NOx emission levels. The limited amount of transient emission test data available (Table 2-21) indicates that levels of about 3.0 g/BHP-hr are already achievable. This one piece of emission test data is not conclusive evidence that all IDI HDDEs can meet the 3.4 g/BHP-hr NOx target level in their present configuration. However, it does provide evidence that IDI HDDEs require at most small reductions to meet a 3.4 g/BHP-hr target level, which should be achievable through minor steps such as a small amount of injection timing retard or perhaps the use of electronic engine control (EEC). Thus, compliance with a 4.0 g/BHP-hr NOx standard appears to be relatively straightforward for IDI HDDEs.

b. DI HDDEs

i. BSFC Improvements

As mentioned above in Section C.2.b.ii with respect to the 1987 standards, general fuel efficiency improvements cause proportional NOx emission reductions by reducing the amount of fuel consumed over the test cycle. Table 2-23 of the above mentioned section shows one analyst's projections of engine fuel consumption improvements in the late eighties and early nineties, yielding some idea of the magnitude of the values being discussed. As can be seen from Table 2-23, efficiency improvements between 1987 and 1992 are expected by EEA to be 7-8 percent for medium and heavy HDDEs. This would represent roughly one-fifth of the 30-40 percent NOx reduction required by the 4.0 g/BHP-hr standard. A similar reduction should occur in particulate emissions as well, as will be mentioned in Section F below. DDA experience with its 6V-92TA appear to roughly confirm these projections, at least for two-stroke engines.[25]

It should be noted that use of EEC is not mentioned in Table 2-23. This technology was not considered because EEA assumed that it's use would be optimized for NOx control rather than improved BSFC, which is also the orientation being taken here.

ii. NOx Control

To comply with a 4.0 g/BHP-hr NOx standard, manufacturers of DI HDDEs are expected to use various combinations of the following technologies: advanced charge air cooling, electronic engine controls (EECs), and possibly small amounts of exhaust gas recirculation (EGR) and/or timing retard. These are discussed below.

NOx emissions are a strong function of peak combustion temperature, which, in turn, depends in part on the initial temperature of the combustion chamber air. Turbocharging, which is used on most DI HDDEs, increases the inlet air temperature significantly above ambient levels. The actual temperature increase is a function of the turbocharger design and operating condition, but a range of 100-200°F is fairly representative. Charge air cooling reduces the temperature of the turbocharged air, increasing the mass of air able to be pumped into the cylinder. Charge air cooling using engine radiator water as the cooling medium (referred to as connected circuit) can cool inlet air to about 185-215°F. Similarly, charge air cooling using a separate radiator system (separate circuit) can reduce inlet air temperatures to about 140-170°F, while using ambient air as the cooling medium (air-to-air) can reduce inlet air temperatures to 110-120°F.

Data published by DDA can be used to estimate the effect of separate circuit and air-to-air charge air cooling.[25] DDA data indicate that at 5.0 g/BHP-hr NOx, separate circuit charge air cooling provides a 2.5 percent fuel economy improvement over connected circuit charge aircooling at the same NOx level. Air-to-air charge air cooling provides a six percent improvement under the same NOx level. While the author did not indicate the reduction in NOx level at constant fuel economy (i.e., BSFC), this reduction can be estimated from the fuel economy data.

As discussed in Section D.3.b. below, a reduction in NOx from 6.0 to 4.0 g/BHP-hr via timing retard has been estimated to cause roughly a 4.5 to 8 percent increase in BSFC*.[25d]

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* It should be noted that NAS labeled the lower limit of this BSFC penalty as that indicative of "advanced" NOx control technology. However, this advanced technology did not include EEC or improved charge air cooling. It only represented the lowest BSFC increase derivable from data available in 1980, which probably meant combustion chamber and fuel injection designs which minimized the impact of timing retard on BSFC. Therefore, the entire range is applicable here.

Since DDA held NOx levels constant, timing must have been advanced to increase NOx emissions after the addition of improved charge air cooling. Retarding timing using the above NOx/BSFC relationship to the point where BSFC is at its original level can be used to determine the equivalent NOx reduction of the charge air cooling at constant BSFC.

For separate circuit charge air cooling, the 2.5 percent fuel economy increase at constant NOx translates into a 0.5-1 g/BHP-hr NOx reduction at constant BSFC, or an 8-17 percent reduction in NOx emissions at 6 g/BHP-hr. For air-to-air charge air cooling, the six percent fuel economy increase is equivalent to a 1.5-2.6 g/BHP-hr reduction in NOx, or a 25-40 percent reduction at 5 g/BHP-hr NOx. These figures must be considered rough estimates since the actual NOx levels were not published (and no other emission data on the effect of such technology are publicly available) and the NOx/BSFC relationship resulting from timing retard may be quite different for the two-stroke 6V-92TA than the group of HDDE engines examined by NAS. However, they do indicate that improved charge air cooling has the potential for providing much and possibly all of the NOx control required by the 4 g/BHP-hr standard.

EEC technology was briefly discussed above with respect to the 1987 standards. The various HDDE manufacturers appear to be at different stages of developing EEC technology. However, by 1990 all HDDE manufacturers are expected to have EECs on some or all of their engines.

DDA appears to be the closest to implementing EECs. By mid-1983, DDA had already accumulated the equivalent of 5.5 million miles on EEC-equipped prototype engines and 75 trucks will test this technology on the road during 1984. Limited production is expected to begin in 1985. Among other parameters, this system precisely controls fuel governing and injection timing at any engine speed, load, and coolant temperature.[25]

The data published by DDA again gives some indication of the NOx control potential available with EEC technology.[25] There, EEC technology is shown to improve BSFC by eight percent on a connected circuit cooled engine at 6.0 g/BHP-hr NOx relative to a mechanically controlled engine. Again using the relationship between BSFC and NOx level for timing retard, EEC could be expected to be able to reduce NOx 2-3.5 g/BHP-hr, or by 30-60 percent at 6.0 g/BHP-hr NOx. These figures may be somewhat overstated, since the presence of EEC could affect the effect of an across-the-board timing retard on BSFC. Still, they indicate a large NOx control potential.

The percentage reductions estimated for both improved charge air cooling and EEC would not likely be directly additive, but would be somewhat lower due to interactions between the two techniques. It should be noted that neither of these two technologies would be expected to increase particulate emissions, which should follow BSFC and remain roughly constant.

The use of EGR for NOx control is a well proven technology for LDDs, but has not been widely used on HDDEs*. Although publicly available data on the effectiveness of EGR on HDDEs is limited, a reasonably good example of the effectiveness of EGR on medium HDDEs is given in Table 2-21. For example, EGR on the naturally aspirated Caterpillar 3208 reduces NOx about 60 percent. Also, although not quite as dramatic, a reduction of 16 percent can be seen for comparable versions of GM's 8.2L turbocharged engine.

One drawback of EGR is that LDD emission test data and a limited amount of HDDE emission test data indicate that controlling NOx with EGR increases particulate emission levels, often by a greater percentage than the percentage reduction in NOx emission.[15,25a] Recent LDD data show this effect to be decreasing, [2], but the carryover of this improvement to DI engines may not be straightforward. Electronically controlled EGR would certainly mitigate some of this increase in particulate, but whether or not it can be completely eliminated is unknown at this time.

Unlike improved charge air cooling and EEC, which manufacturers are moving toward for market reasons, EGR would only be added for emission control purposes. While EGR should be technically feasible for HDDEs, its implementation faces a number of practical hurdles.

For example, the recycled gas will contain particulate matter which will be spread throughout the intake air in the cylinder. This will increase the contact of particulate with the cylinder walls and could raise particulate levels in the engine oil and reduce oil change intervals. Also, since the recycled gas would have to be introduced upstream of the turbocharger on a turbocharged engine, increased turbocharger wear may occur. If an aftercooler is present, it's surfaces could be fouled by recycled particulate. A system which eliminated the presence of particles in the recycled exhaust would solve these problems, but such a system could be difficult to design. Some possibilities are: 1) an oil bath filtering system, 2) placing a small trap-oxidizer in the EGR circuit, or 3) taking the exhaust from a point after the exhaust trap-oxidizer.

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* Several manufacturers have suggested that for full efficiency an EGR system will require the use of an EGR cooler, performing the same function as charge air cooling.[22] The need for such a cooler would likely depend on the overall EGR rate being used; the higher the rate, the greater the need. As will be seen below, EGR is not expected to be used on many HDDEs to meet a 4.0 g/BHP-hr standard, and even then at low overall rates. Therefore, at this time, EPA does not have adequate data on hand to judge whether an EGR cooler is necessary.

The one production EGR system on a HDDE is on the Cat 3208. However, this system provides EGR primarily at light loads for the control and the engine is naturally aspirated. Thus, it does not address many of the above-mentioned concerns. Mercedes-Benz uses EGR on their turbocharged 300D passenger car, but the useful life of this vehicle is well below that of DI HDDEs.

Overall, EGR has more drawbacks associated with it compared to the other two techniques mentioned above. Thus, its use will likely be limited, particularly on turbocharged and aftercooled engines. Even when used, the overall EGR rate will likely be low, to minimize its effect on particulate emissions and durability.

In summary, improved charge cooling and EEC, coupled with general BSFC improvements, appear to have the potential to provide more than the necessary 30-40 percent reduction in NOx emissions required by the 4.0 g/BHP-hr. Where one or both of these technologies is not sufficient, additional timing retard and/or EGR may be used. The use of an efficient trap-oxidizer for particulate control should mitigate any particulate increase resulting from use of these latter two techniques. However, use of either of these two less desirable technologies is expected to be the exception in the short-term and negligible in the long-term.

3. Other Impacts of the Proposed 1990 NOx Standard

a. Hydrocarbon Emissions

There is some indication that charge air cooling may very slightly increase HC emission levels. Therefore, advanced charge air cooling might lead to slightly higher HC emissions as well, apparently due to the fact that the air entering the cylinder is cooler.

Turning to EGR, LDD data indicate that relatively high EGR rates will also lead to higher HC emission rates. However, the EGR rates used by DI HDDEs should be well below those used by LDDs, given the practical problems of using EGR in DI engines mentioned above. Also, as evidenced by Caterpillar's use of light-load EGR on one of its 3208 models, EGR can actually be used as an explicit HC control strategy. Therefore, little, if any, adverse effect on the HC emissions should occur due to the small amount of EGR expected to be used.

Finally, electronic controls should decrease HC emissions, if affecting them at all, due to the increased flexibility provided.

Overall, these should be little net change in HC emissions due to a 4.0 g/BHP-hr NOx standard.

b. Fuel Consumption

In a situation where fuel consumption could be optimized, techniques such as advanced charge air cooling and EEC would be expected to provide significant BSFC improvements.[25] However, when optimized for NOx emission control, these BSFC improvements will likely be diminished.

NAS estimated that a 4 g/BHP-hr NOx level would cause a 4.5-8 percent BSFC increase over a 6 g/BHP-hr level. This assumes that timing retard is the primary control technique, though "advanced" (1980-81) combustion chamber designs which reduce the effect of timing retard are also considered.[25d] In their recent report on light-duty diesels, the National Research Council estimated that a 10-15 percent increase in fuel economy would occur with electronic controls.[25e] Also, in a recent paper, GM reported that EEC and improved charge air cooling would improve BSFC 13-16 percent at 4-6 g/BHP-hr NOx levels.[25]

Overall, then, it would appear that no fuel consumption penalty should occur if advanced NOx control techniques are used to meet the 4 g/BHP-hr NOx standard. However, for a variety of reasons, such advanced techniques may not be applied to all engines immediately in 1990. Cost considerations, leadtime constraints, and the timing of model replacement/redesign could lead a manufacturer to choose further timing retard over electronics and improved charge air cooling. If this occurred, then a short-term BSFC penalty of up to 1-2 percent could occur.

E. Technological Feasibility of the Proposed 1990 Particulate Standard

1. Introduction

In addition to the engine-related emission control techniques discussed above with respect to the 1987 particulate and those discussed below with respect to 1990, another method of particulate control is available. It involves the application of an aftertreatment device to a heavy-duty diesel engine. The most developed aftertreatment device is the particulate trap-oxidizer. Other devices, such as electrostatic filters, cylone filters, thermal precipitators, liquid scrubbers, fluidized bed scrubbers and granular filter beds, have been suggested, but their state of development is not well advanced, and need much more development before they could be considered commercially feasible. A trap-oxidizer works by collecting particulate matter from the diesel engine-out exhaust and oxidizing the trapped particulate matter. The oxidation phase (also known as regeneration) is necessary because it is not possible for a trap to collect all the particulate matter emitted by a diesel engine over its lifetime. (A trap designed to hold all of the accumulated particulate would not be viable because of its very large size and because the resulting increased exhaust gas backpressure would be detrimental to engine operation.) In this section, EPA will evaluate the feasibility of this control technology for application to heavy-duty engines.

The initial research and development of diesel particulate trap oxidizers was done by the light-duty diesel vehicle industry. Much of the technology developed by and for this industry has formed the basis for the development of similar technology for the heavy-duty diesel engine industry. Therefore, the discussion of heavy-duty diesel particulate trapping technology will start by summarizing the status of the light-duty trap-oxidizer. This will be followed by a discussion of the applicability of light-duty diesel particulate trapping technology to heavy-duty engines. The third part of this discussion will examine the status of heavy-duty diesel particulate trap technology development and the additional development that is necessary for a particulate trap-oxidizer system to be available for use on heavy-duty diesel engines. The ability of trap-equipped heavy-duty diesel engines to meet a .25 g/BHP-hr trap standard will also be examined.

2. Status of Light-Duty Trap Oxidizer Development

The technical feasibility of light-duty trap-oxidizer use was recently reviewed in two analyses: "Trap-Oxidizer

Feasibility Study"[26] an EPA document, and "Trap-Oxidizer Technology for Light-Duty Diesel Vehicles: Feasibility, Costs, and Present Status,"[27] a document prepared for EPA by an independent contractor. The other major source of information available to the Agency came from the public participation (comprised of public comments and data) that resulted from the proposed standard of 0.2 grams of particulate per mile for light-duty vehicles produced for the 1985 model year (delayed to 1987). Based upon this information, the Agency concluded that light-duty vehicle trap-oxidizers would be technically feasible no later than the 1987 model year. The following is a summary of the data that led to this conclusion. (An EPA regulatory support document, "An Updated Assessment of the Feasibility of Trap-Oxidizers", contains a more detailed, complete report.[28])

To summarize the status of the light-duty trap oxidizer, there are two basic trap-oxidizer designs that can meet the required collection efficiency, backpressure, and durability characteristics. One of them is the ceramic wall-flow monolith trap and the second design is an alumina-coated wire mesh trap. Both trap designs are capable of satisfactory collection efficiencies (70-90 percent for the ceramic wall-flow monolith trap and 50-80 percent for the wire mesh trap) and both can maintain acceptable backpressure over durability accumulations of up to 50,000 miles with properly controlled regeneration.

The wall-flow monolith diesel particulate trap is based on a design similar to the ceramic honeycomb substrate used in light-duty gasoline-fueled-engine catalytic converters. As such, it is a porous, ceramic honeycomb matrix of tubes of which alternate cells of the upstream face are plugged with ceramic. The complementary, alternate cells of the downstream face are also plugged with ceramic and thus there is no direct path for exhaust to flow through the monolith. Rather, the exhaust flow must enter the open cells on the upstream face and then pass through the porous wall (and then out the open alternate cell on the downstream face) which filters the exhaust stream of its particulate matter. The particulate matter collects on the walls (which increases the backpressure through the trap) and must be periodically removed by oxidizing it, which serves to "regenerate" the trap. This oxidation procedure is very important for proper long term trap usage. It will be discussed in more detail in a subsequent paragraph. This type of trap usually contains no catalytic material t alter the temperatures at which oxidation begins.

On the other hand, the wire mesh trap usually contains wire which is coated with alumina which, in turn, is coated with a washcoat of catalytically active metal. The tightly packed mesh traps the particulate and then oxidizes it, thus regenerating the trap more or less continuously.

The second part of trap-oxidizer development concerns the oxidation of the trapped particulate. For non-catalyzed traps, exhaust temperatures in the range of 500-650°C and oxygen levels of 3-4 percent are required for a duration of 2-10 minutes in order for regeneration to occur. A catalyst-based trap will require lower pre-trap exhaust temperatures of approximately 310-350°C. There are two general approaches to regeneration: positive regeneration and self-regeneration. Positive regeneration systems regenerate the trap at a specific point in time by raising the temperature of the particulate in the trap-oxidizer. Methods of positive regeneration include external heat sources (e.g., fuel burner), modification of engine parameters (e.g., air intake throttling), or raising the HC and CO levels in the exhaust for catalyzed traps (e.g, exhaust-stroke fuel injection). On the other hand, self-regeneration relies on attaining regeneration conditions during normal vehicle operation without the activation of any special mechanism. An example of self-regeneration is the continuous use of fuel additives to lower the particulate ignition temperature. Technically feasible regeneration systems for non-catalyzed ceramic wall-flow monolith traps include the fuel burner, electrically heated traps and a trap that is close coupled to the exhaust manifold that uses throttling and EGR for elevating the upstream temperatures.

The fuel burner provides the additional heat necessary for regeneration by igniting an air/fuel mixture immediately in front of the trap inlet. The burner requires a fuel supply and fuel injector, a glow plug or spark plug to initiate ignition, and an oxygen supply. The oxygen may be supplied by a low-pressure air pump (air-fed burner) or by residual oxygen present in diesel exhaust (exhaust-fed burner). Alternatively, the burner can heat the entire exhaust gas flow (in-line burner), or can heat just the trap itself while the exhaust gas is routed away from the trap (bypass burner). All of these options have been investigated by various manufacturers.

For the catalyzed wire mesh traps, there are several technically feasible regeneration approaches. These include exhaust-stroke fuel injection, limited throttling with excess EGR and limited throttling without excess EGR.

The basic concept of self-regeneration through exhaust-stroke fuel injection is to create the diesel equivalent of a misfire by injecting additional fuel into one cylinder at bottom dead center at the beginning of the exhaust stroke. This fuel is "cracked" into lighter HC and CO molecules by the heat and pressure which still exists in the cylinder. The HC and CO are then exhausted on the piston upstroke and oxidized by the precious metal catalyst on the wire mesh trap. Johnson-Matthey has stated that the exothermic reaction of the HC and CO produces a temperature rise of approximately 150-200°C. The catalyzed wire mesh trap oxidizes particulate at approximately 350°C, so exhaust-stroke fuel injection can initiate regeneration for catalyzed wire mesh traps at exhaust temperatures as low as 200°C. Limited throttling (one or two cylinders) with or without excess EGR are two other methods of delivering additional quantities of HC and CO to the catalyzed trap. (These systems would obviously not work for non-catalyzed traps.)

The utilization of fuel additives to induce regeneration has also been examined. This concept involves the introduction of a catalytically active fuel additive (usually a metal compound) upstream of the trap, thus catalyzing oxidation of accumulated particulate. This fuel additive introduction could be continuous or intermittent. An example of a continuous additive introduction system would be one that had the additive mixed with the fuel, either during refueling or earlier in the fuel distribution system. An example of an intermittent additive system would be a mechanical injection system that would place the additive either into the onboard fuel after it leaves the fuel tank or into the exhaust stream.

Because additive systems can be mechanically simpler, requiring fewer vehicle/engine modifications than the other regeneration systems, they may be preferred by some manufacturers. The eventual use of fuel additives, however, is conditional upon the resolution of trap plugging and environmental concerns. For example, certain test results indicate that the trap may retain most of the catalyst additive material. But if there are catalyst emissions, the question of whether they would represent an unacceptable environmental hazard would need resolution.

The problem of how the additive will be introduced to the fuel must also be resolved. Mixing the additive into the fuel at the refinery raises concerns about the fuel distribution. For example, will all diesels use the fuel with additives? If so, the non-trap equipped vehicles would emit all of the catalyst material. Will a more costly and complex method of separate fuel distribution be used for trap and non-trap equipped engines? The other alternative, on-board introduction of the additive, is less complex from a fuel distribution standpoint, and is presently being explored by various manufacturers. It too presents some unanswered questions such as potential toxicity of an additive that would have to be handled and stored onboard a vehicle.

Positive regeneration requires a control technique to determine when regeneration is required, so as to initiate the regeneration process and to confirm that regeneration is complete. To date, Johnson-Matthey has designed a regeneration control algorithm for HC and CO enrichment with its catalzed wire mesh trap. A manually controlled fuel burner regeneration system has also been developed by Ford. The primary work remaining will be the development of a fully automated system and the additional testing of prototype systems needed for system refinement. None of the tasks associated with positive regeneration control systems are judged to be technically infeasible.

The Agency considers the manufacturers to be in the final stage of light-duty trap-oxidizer development. Although a large amount of the information about trap-oxidizers is proprietary, what information is publicly available indicates that final development and optimization are underway. Daimler-Benz's 1985 certification plans confirm this.[29] Daimler-Benz plans to start certification testing of its 3L 5-cylinder turbo diesel equipped with a particulate trap to meet California's 1985 emission standards. The full details of Mercedes' trap technology have not been publicly released, only the general design. According to this general information there will not be a separate high-temperature burner; the accumulated particulate will be oxidized by self regeneration, most likely through partial throttling at designated times. Although the other vehicle manufacturers have not yet identified a trap/regeneration control system to be committed to production, EPA believes they are not too far behind Daimler Benz's trap development to jeopardize compliance for 1987.

The trap-oxidizer analysis by EPA's independent contractor[27] confirms the Agency's belief that light-duty trap technology is at a very advanced stage. The analysis identified three trap-oxidizer systems which it considered to be at an advanced stage of development: 1) ceramic wall-flow monolith trap/regeneration with fuel burner, 2) catalyzed wire mesh trap/regeneration by HC and CO enrichment (such as exhaust-stroke fuel injection), and 3) ceramic wall-flow monolith trap/self-regeneration using fuel additives. This study concluded that there are no technical uncertainties regarding the feasibility of the ceramic monolith/fuel burner system. It considered successful development of the catalyzed wire mesh/HC and CO enrichment system to be "highly probable" (although the occurrence of increased sulfate emissions has not been resolved) and development of the ceramic monolith/fuel additive system to be "probable" in the near term. Both of these systems would be preferred if feasible, due to their greater simplicity and lower costs. If these systems did not prove to be feasible, then the fuel burner could be adopted industry-wide. EPA agrees with these conclusions and believes that successfully functioning trap-oxidizers will be available for 1987 LDV use.

3. Technical Evaluation of Light-Duty/Heavy-Duty Differences

Much of the particulate trap technology described in the previous section can be adapted to heavy-duty engines. However, while the heavy-duty industry can make use of existing trap technology, there are specific differences between light- and heavy-duty applications that must be considered in designing a heavy-duty trap oxidizer. What these differences are and how these unique design needs can be resolved will be discussed in the following paragraphs.

An obvious light-duty/heavy-duty difference is the engine size and load factor. The larger and more heavily loaded HDE has a higher exhaust volume and mass flow rate, thus increasing the amount of particulate in the exhaust. In order to compensate for the increased flow rate, the heavy-duty trap size must be increased to ensure that the backpressure doesn't rise too quickly, or regeneration occur too frequently. This larger trap size can be accomplished by using larger traps (which could present mechanical durability problems due to greater stresses) or by using more than one trap. The larger trap size also makes auxiliary heating for trap regeneration more difficult on HDEs than on LDEs; heating evenly over a larger surface can be a problem. However, the larger size of a HD vehicle does ease the housing problem of the larger heavy-duty trap. The larger HDV also allows for more variation in the trap geometry. Another problem is with temperatures. Temperature considerations must be divided into two areas of discussion that relate to turbochargers. Exhaust gases expand in the turbine portion of a turbocharger in an engine so equipped, which lowers the temperature of the exhaust stream. Therefore, non-turbocharged engines and exhaust systems upstream of a turbocharger have higher temperatures than found in exhaust systems downstream of a turbocharger. Most heavy-duty engines currently produced are equipped with a turbocharger.

For the case of a non-turbocharged engine and in exhaust system locations upstream of the turbocharger, HDDEs yield higher exhaust temperatures than LDDEs due to sustained high load/high speed operating conditions typical of HDDEs. A trap may melt when exposed to these sustained higher temperatures and thus, heavy-duty traps must be designed to withstand them. During operation at high temperature modes, it may be possible for self-regeneration to occur because the required temperature range of 560°-650°C may be reached. However, because the operating conditions which yield these high temperatures may not occur routinely, self-regeneration cannot be relied upon; a regeneration system must also operate when the heavy-duty trap is exposed to routine cooler exhaust temperatures. For example, HD trucks frequently idle for long periods of time, yielding lower exhaust temperatures.

In the case of a turbocharged engine, in locations downstream of the turbocharger, the necessary regeneration temperature may not be attained as required, and the accumulating particulate would increase the backpressure to the detriment of engine operation. The regeneration technique must therefore compensate for the low-temperature periods by either increasing the exhaust-gas temperature (e.g., using a fuel burner) or decreasing the required oxidation temperature of the particulate (e.g., using fuel additives or a catalyzed trap). In short, although HDE regeneration problems are similar to those observed in light-duty, trap sizing and temperature ranges are special problems that need to be accommodated.

Another major difference between light-duty and heavy-duty diesel operation is the useful life of an engine. The useful life of a LDDV is approximately 100,000 miles while a HDDE's useful life ranges from 110,000 to 290,000 miles, depending upon the service usage. In-use engines can conceivably run much further. The longer on-road life of a heavy-duty diesel engine requires that substantially more durability be designed into the trap. This will require that the heavy-duty industry perform sufficient durability testing under conditions which simulate in-use HDE operating conditions.

Another difference that needs to be addressed is the potential increase in ash accumulation in the trap because of both the heavy-duty diesels' longer useful life and higher exhaust flow rate through the trap. Diesel fuel and lubricating oil contain metallic additives that are non-combustible and that can accumulate in the particulate trap. The accumulated ash does not oxidize, and thus contributes to increased backpressure and, in extreme cases, can cause trap clogging. Cummins researched this problem[30], conducting accelerated bench tests to simulate actual engine operation. Their research yielded an exhaust ash emission rate of 17 g/1,000 km for a typical HDDE. Further research is necessary because the bench work of Cummins does not necessarily characterize an actual heavy-duty diesel engine. If actual heavy-duty tests show ash accumulation to be a real problem, possible solutions include changing the trap design and flow path, or reducing or changing the metallic additives in the fuel and oil.

In conclusion, conditions which are specific to the HDDE environment must be considered and dealt with when extending light-duty trap technology to heavy-duty applications. While EPA does not deny that considerable development effort will be necessary on the part of the heavy-duty industry, EPA does not consider the problems to be without solutions. The feasibility of light-duty traps, combined with the ongoing research and development of a heavy-duty trap, lead EPA to the conclusion that traps should be feasible for heavy-duty use.

In fact, early HDDE trap development work is now underway, and is discussed next.

4. Status of Heavy-Duty Trap Technology Development

Data discussed in this section comes from several sources. After the first NPRM for HDDE particulate emission standards was published (46 FR 1910, January 7, 1981), EPA received comments from the heavy-duty industry describing the status of their current trap work. Representatives of most HDDE manufacturers have also recently met with EPA staff to further discuss their development programs. (Much of the information about test results and the specific trap-oxidizers being tested is deemed by the manufacturers to be of a proprietary nature; only that information that is publicly available can be reviewed here.) Finally, EPA has contracted with an independent researcher to study the problems of HDDE trap development.

The January 7, 1981 NPRM proposed a trap-based standard of .25 g/BHP-hr for the 1986 model year. In their comments, the manufacturers were in agreement that heavy-duty "trap-oxidizer technology is still in the development stage, and it will certainly not be ready for introduction in production heavy-duty vehicles by the 1986 model year."[31] The significant question addressed by this analysis is when traps will be ready. A leading potential trap manufacturer stated to Mack that "traps will not be available for heavy-duty engines until 1989."[32] The traps being tested for heavy-duty application are similar to the promising light-duty traps with an exception that will be discussed in the following paragraph; they include both catalyst and non-catalyst ceramic monolith, metal mesh, ceramic foam, ceramic fiber, and coil-type filters. Due to the high exhaust flow, the heavy-duty traps being evaluated are typically larger than a light-duty trap, increasing its total capacity. The collection efficiency of the trapping device, however, is fairly constant for both light-duty and heavy-duty. Although Cummins claims that current traps are not achieving consistent collection efficiencies, it is generally accepted that the basic designs can meet the required collection efficiency characteristics.

In addition to these light-duty trap designs that are being adapted to heavy-duty requirements, there is a solica-fiber candle/catalyst design that was developed especially for heavy-duty use. This system is produced by Damiler-Benz; the limited available data on its is presented in a report to the EPA by a independent contractor,[33], and is summarized here. The trap consists of a number of candle-like filtering elements made of treated silica-fiber yarn woven on a porous metal tube. The "candles" are arranged axially in a container. The exhaust gas flows into the container, through the candles radially (outside to inside), depositing the particulates in the yarn as it exits through the centers of the tubes. Daimler-Benz reports[34] that this trap has a high collection efficiency and low backpressure. Regeneration is accomplished by injecting a powdered oxidation catalyst into the exhaust stream at a temperature high enough for oxidation to occur. The control and actuator system includes an electronic control system, a backpressure sensor, an exhaust temperature sensor, and an engine rpm sensor.

The second and third parts of a trap-oxidizer system, regeneration and its control technique, are the major focus of industry's research. The heavy-duty operating conditions, especially the frequent and oft times lengthy idling periods, prevent self-regeneration from occurring on a regular basis because of insufficient exhaust temperatures. Therefore, either a positive regeneration system is required or a means for lowering the temperature of self-regeneration is necessary. The regeneration methods being evaluated are similar to those discussed in the previous section for light-duty, plus the Daimler-Benz method. Fuel additives are being investigated as an appealing method of regeneration due to the simplicity of the system and the resulting low cost to the engine manufacturer. The use of fuel additives should lower the temperature at which the trapped particulates oxidizes, but Daimler-Benz reports that testing has not yet produced successful or reproducible results.[34] Also, the same unresolved questions of light-duty fuel additive use apply to heavy-duty use: the method of introduction of the additives to the fuel, potential environmental consequences, and the possibility of trap plugging.

The use of catalyzed traps has been examined and/or tested by several manufacturers. A catalyzed trap's regeneration system, such as late fuel injection, inlet throttling, or exhaust restriction, raises the HC and CO levels in the exhaust. The catalyst oxidizes the HC and CO and the additional heat burns the collected particulate. The drawback of a catalyzed trap is the formation of sulfate by the catalyst: heavy-duty operating conditions have been observed to significantly increase sulfate production from a catalyzed trap. However, the increased sulfate production observed during heavy-duty testing may be a function of the type of catalyzed trap being used. Presently the traps being evaluated for heavy-duty are larger light-duty traps that haven't yet been fully adapted for heavy-duty usage. For example, Johnson-Matthey believes that the high-sulfate problem is associated with the catalyst noble metal loading. Work is now underway to create a reformulated trap to eliminate the problem of sulfate production. The heavy-duty trap developed by Daimler-Benz has a tendency to retain the catalytic additive, resulting in plugging and increases in backpressure after 100,000 miles. This design would require a replacement of the trap if the plugging problem could not be solved.

The most developed regeneration system continues to be burner regeneration, in conjunction with uncatalyzed traps. Although complex, a burner system appears to be the type of regeneration that will be viable at the nearest future date. The heavy-duty burner system is similar to light-duty burner regeneration systems, although a heavy-duty vehicle would likely require a larger system.

The silica-fiber candle/catalyst system also appears to be a well developed technology. Daimler-Benz has accumulated more than 250,000 kilometers of testing on it and projects that it will be ready for production in 1989.[33]

Development of an automatic regeneration control system remains the next major step. Except for the instances where self-regeneration occurred, all of the traps tested to date with heavy-duty engines have had their regenerations controlled manually. Industry's work in this area is purportedly constrained by the fact that "automotive trap technology is in its infancy."[35] GM in particular believes that "optimization of a control system cannot be done until sufficient data are available from a suitable trap operated under all anticipated types of driving conditions."[31] GM has tested numerous trap-oxidizers on both engine dynamometers and in vehicles, and has observed trap failures involving thermal cracking of the trap material. GM claims that until a trap can be designed that will fulfill all the necessary performance requirements such that the system can be completely characterized, a control system cannot be developed. This conclusion, however, probably represents the results of worst case durability testing, and fails to consider the moderating effects of a properly functioning regeneration control system. The Agency agrees that the heavy-duty engine/trap/regeneration system's operational limits must be thoroughly defined. However, a functioning regeneration system should help prevent thermal failure of the trap, as certainly will other design and material modifications.

Any production regeneration control system must also include sensors, actuators, and a programmed central processing unit for a fully automated system. This equipment is already being developed for light-duty trap regeneration control systems, and should be easily applicable to the heavy-duty trap. In addition, the heavy-duty industry is also evaluating the application of electronically controlled fuel-injection systems (see above), which would facilitate the application of the control logic for the regeneration system.

In summary, a heavy-duty trap regeneration system can probably be designed to meet future regulatory needs. As the light-duty industry progresses towards the complete development of a regeneration control system, the heavy-duty industry can probably adapt this technology to its own needs. However, there is a definite lack of data from the heavy-duty diesel engine industry on particulate traps, especially relative to the light-duty diesel industry. This is probably due to the fact that the light-duty industry has had to work towards a particulate standard that essentially required traps whereas the heavy-duty industry has not had that incentive.

To obtain some HDDE trap data the Agency contracted with Southwest Research Institute (SwRI) to test a trap-oxidizer system on a heavy-duty engine. The objectives of the testing were: 1) to evaluate the effectiveness of a low-mileage trap installed on a HDE, 2) to develop a method of regeneration, and 3) to characterize the emission levels during trap use compared to the baseline levels. An in-depth results of the investigation are available in the final report by SwRI[36]; the summary of the testing results is included here.

A Corning catalyst was tested on a DDAD 6V71 diesel coach engine and also in a 1980 GMC RTS-II coach vehicle. The engine was a 2-stroke direct-injected diesel engine which used a blower for scavenging. The trap was a ceramic wall-flow monolith type and regeneration was accomplished with an in-exhaust-pipe burner. The regeneration was manually performed at idle, with the burner capable of raising exhaust temperatures from 120 to 700°C.

The trap was found quite effective in reducing particulate emissions. During transient testing of the engine, the trap reduced total particulate emissions by about 65 percent; chassis testing of the coach vehicle equipped with a trap yielded a 92 percent reduction in particulate emissions. The trap reduced steady-state particulate emissions from the engine by an average of 79 percent. Smoke emissions were reduced by almost 100 percent under all modes of operation. The trap was effective in reducing carbonaceous particulates, although it had a variable effect in reducing the soluble organic fraction (SOF) of the total particulate. Differences between observed brake specific fuel consumption (BSFC) with and without the trap were minimal. There was, however, a thermal cracking failure of the trap following a chassis test when the trap exit temperature peaked at 990°C (occurring 66 seconds after the burner was shut off).

The SwRI test results indicate that sufficient trap efficiency can be obtained with a heavy-duty trap, for both steady-state and transient testing. A method of regeneration was also developed; some problem was seen with thermal cracking, but as noted above, further development and refinement of an automatic regeneration control system will help prevent thermal trap failures.

Finally, to date there has been some concern as to the fuel economy effects of trap-oxidizer use. As particulate are collected, an increase in the exhaust back pressure occurs, which may result in fuel economy losses. Since minimal differences in BSFC were noted by SwRI with the trap as compared to the baseline levels, EPA believes that a zero to 2 percent fuel consumption penalty is the very worst penalty which will be observed with HD traps. Carefully controlled regeneration of the trap should minimize the fuel economy impact. For example, Cummins notes that "if the trap can be regenerated at 100 mile intervals, a 1.6 percent fuel consumption penalty will be incurred."[35] As with the thermal trap failures, the refinement of an automatic regeneration control system is critical to minimize increased fuel consumption associated with trap oxidizers.

5. Design Target and Degree of Requisite Trap Application

A trap standard of .25 g/BHP-hr has been proposed for 1990 HDDEs. This emission level is dependent on several factors and can be calculated from the following formula, which has already been described in a slightly different form.

$$MPL = ETL \times DF \times AQL \times (1 - Eff)$$

Where:

MPL = maximum pass level

ETL = engine out design target level

DF = deterioration factor

AQL = SEA adjustment factor

Eff = trap efficiency

The target level, 0.47-0.51 g/BHP-hr, and the AQL factor, 1.10-1.15, apply to an engine-out emission level of .6 g/BHP-hr, as previously discussed. The deterioration factor represents the deterioration for engine-out particulate and also the deterioration for the trap. The DF for the engine-out PM was determined to be 1.1 on a multiplicative basis. To determine the DF for particulate traps, it is necessary to perform durability testing. Although no such testing has been performed for heavy-duty traps, the deterioration rate for light- and heavy-duty traps is assumed to be similar. SwRI tested two types of traps, a ceramic trap and a wire mesh trap, operating both traps in LDVs over 50,000 miles of service accumulation. No significant deterioration of particulate emissions occurred over the 50,000 miles of testing. Thus, a DF of 1.0 is assumed for traps. This is reasonable, particularly for wall-flow ceramic traps which apparently are currently the most preferred, since there is no mechanism for small reductions in efficiency. If cracks develop the efficiency will effectively be zero. However, this is a reliability problem which is expected to be solved by 1990. Deterioration thus appears to be zero.

The trap efficiency is the most variable factor that effects the emission level. The ceramic wall-flow monolith trap is the more efficient trap with a collection rate ranging from 70 to 90 percent: this is a very conservative range since most of the testing with this type of trap has yielded efficiencies of greater than 90 percent. The wire mesh trap's collection efficiency ranges from 50 to 80 percent. The collection efficiency of the silica-fiber candle trap is not presently available. The differences in trapping efficiencies yield large differences in particulate emission levels. An 80 percent efficiency has been chosen to represent a trap efficiency that is in this range, but would be quite low if wall-flow traps were used.

Applying these factors to the above formula, the calculated emission level is 0.14-0.17 g/BHP-hr. Thus, traps will not be required on all engines; the technically most difficult applications will be able to be excluded from trap usage, which is desirable given the new nature of this technology. With averaging, the number of trap-equipped heavy-duty engines can be reduced to roughly 70 percent, thus increasing the averaged particulate emission level to 0.24-0.26 g/BHP-hr, bracketing the 0.25 g/BHP-hr standard proposed.

Limiting consideration to only highly efficient, ceramic wall-flow monoliths, even lower levels would be achievable. Using a reduction efficiency of 90 percent in the above calculations would yield achievable levels of 0.07-0.09 g/BHP-hr, or low enough to comply with a 0.10 g/BHP-hr standard. Of course, under this standard, essentially all vehicles would require trap-oxidizers.

6. Summary

Trap technology, while not presently available for production heavy-duty application, should be technically feasible by 1990. To date, heavy-duty trap development efforts have been limited. In light-duty, substantial development was only stimulated by the proposal and promulgation of trap-based standards. Furthermore, with industry's vigorous pursuit of a trap-oxidizer system, a 1990 HDDE trap-based particulate standard should be meetable. This follows from the fact that trap-oxidizers will be in production on many light-duty diesels no later than 1987. Secondly, as discussed above, light-duty trap technology can be adapted for heavy-duty use. Additional design effort is necessary but the problems and differences from light-duty applications are easily identified, and should be solvable by system design modifications, optimizations, and the application of known technologies. The heavy-duty industry has six years of leadtime until 1990 to refine technologies and incorporate these changes. At least three of these years will follow widespread production of light-duty traps. It stands to reason, however, that a 1987 implementation date, the year traps will be produced on LDVs, is too soon to be feasible for heavy-duty given the unique problems to be solved.

In summary, based upon the current state of trap development, there appears to be sufficient time for the manufacturers to design, develop, and prepare trap-oxidizers for 1990 model year HDDEs. Development of an automatic regeneration control system and solution of potential ash accumulation problems remain the critical tasks left for the heavy-duty industry.

F. Achievable Non-Trap Particulate Levels in 1990

To provide additional pertinent information to the rulemaking process, the feasible level of a 1990 non-trap particulate standard, in conjunction with the proposed 1990 NOx standard of 4.0 g/BHP-hr, was evaluated. That analysis appears below.

1. Effect of a 4.0 g/BHP-hr NOx Standard

The first step in this analysis is to determine the effect, if any, that a 4.0 g/BHP-hr NOx standard would have on

1987 particulate levels. This primarily means addressing improved charge air cooling and EEC, since EGR and additional injection retard are expected to be needed on only a few engines and their impact can be ignored here.

As mentioned in Section D.2.b.ii. above, when used to their fullest NOx control extent (i.e., at constant BSFC), neither improved charge air cooling or EEC is expected to reduce particulate emissions. However, it is possible that this extent of NOx control will not be needed, and BSFC and particulate emissions could both improve. As it is unknown how the size of the particulate reduction would compare to the size of the BSFC reduction, it is not possible to quantitatively estimate the potential particulate reduction. However, given the size of the initial BSFC improvements, any net particulate reduction is likely to be small (i.e., less than 10 percent).

In addition to the effect of these specific NOx controls, there is the general effect of BSFC improvements on all emissions. In Section D.2.b.i. above, one analyst's estimates were described, showing a 7 to 8 percent BSFC improvement between 1987 and 1992. Using this as a rough approximation, a 5 to 10 percent reduction in particulate emissions should be achievable via use of fuel efficiency techniques.

2. Engine-Related Particulate Controls

Engine-related particulate controls in the 1987 timeframe were already discussed in Section C. 2. above. Further reductions beyond these could come from five areas: 1) further improvements to general combustion chamber design, 2) advanced fuel injection techniques, including high pressure injection, 3) cylinder heat retention technology, and 4) fuel modification, particularly use of methanol. The particulate reduction potential in each of these areas is dicussed below. Another technique, turbocharging, will not be discussed simply because the majority of DI HDDEs are already turbocharged.

a. Combustion Chamber Design

Modifications to basic combustion chamber designs were already discussed previously with respect to compliance with the 1987 particulate standard. While three additional years of leadtime would certainly provide the opportunity for further improvement, the general evidence available appears to indicate that across-the-board particulate reductions are fairly small. Parametric studies, like that conducted at Michigan Technical University (MTU) for EPA, [37] have simply not discovered standard design criteria which could lead to significant particulate reductions by 1990. At the same time, a large number of researchers are investigating the formation of particles in diesel engine on a fundamental level and the results of this work may lead to reductions in the future. Thus, at the present time, this area does not appear to hold significant promise in providing large particulate reductions in this decade.

b. Fuel Injection System Design

Two aspects of the HDDE fuel injection system appear to hold some promise in reducing particulate emissions. One is increased injection pressure (i.e., injection rate) and the other is the shape of the fuel injection rate over its duration. The reader is referred to Reference 37 for a detailed description of these modifications.

With respect to increased injection pressures, Figure 2-9 shows its effect on emissions and BSFC on 6 modes of the 13-mode cycle (3, 4, 5, 9, 10, and 11). The peak injection pressure of the standard (low pressure) pump was 40.0 MPa, while that of the high pressure pump was 46.5 MPa. As can be seen, significant reductions in total particulate matter (TPM) occurred at the high injection pressure. Focusing on NOx emissions first, a timing of about 14° BTC with high injection pressure would have held NOx emissions constant. At this timing, BSFC should also be roughly constant between the two injection pressures. However, particulate emissions (both solids and soluble organics) decrease 25-60 percent, depending on the mode.* While these reductions may not be repeatable on every engine design, they are indicative of the potential reductions available via high pressure injection. Also, a peak pressure increase of 16 percent is not large and should be achievable by 1990.

With respect to the shape of the fuel injection rate curve over the duration of injection, the work performed at MTU suggests three changes to further lower particulate.[37] One, use of a zero sac volume should lower soluble organics. Two, injecting the fuel as rapidly as possible should reduce the carbonaceous portion of total particulate by enhancing rapid air-fuel mixing. Three, the initial injection rate should be only high enough for a time to avoid poor mixing, since too high an initial injection rate can lead to increased solids formation. These changes, coupled with high injection pressure, are projected by MTU to reduce carbonaceous particulate by 70 percent overall, with lower but still significant reductions in the soluble organics.

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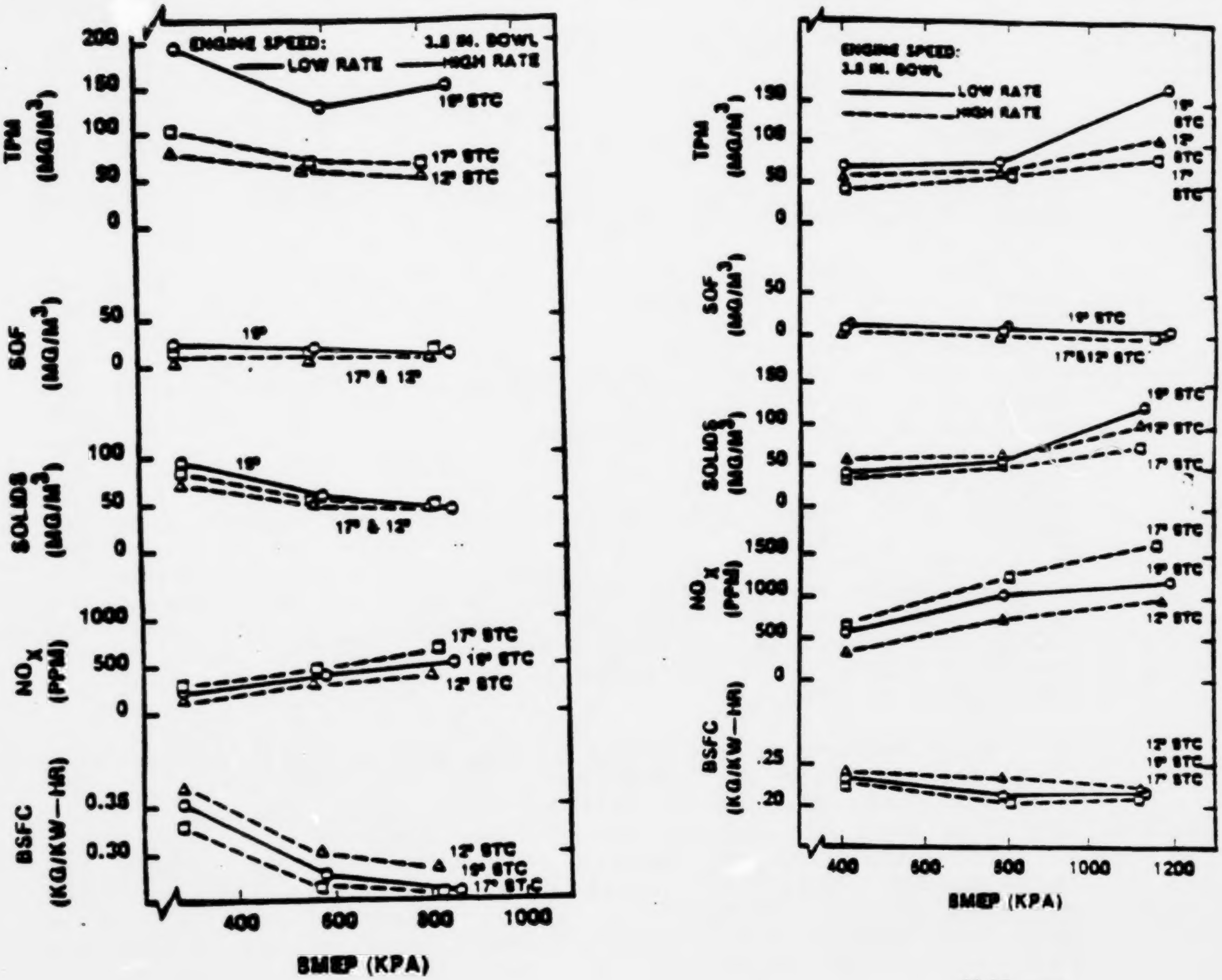
* A third component of total particulate, sulfates, is not shown in the figure.

Figure 2-9

Effect of Increased Rate of Injection
and Retarded Injection Timing. (1)



1270 rpm

2100 rpm

(1) Taken from Reference 37
TPM = Total Particulate Matter.
SOF = Soluble Organic Fraction.

While increases in injection pressure of 15-20 percent should be achievable in the 1990 timeframe, affecting the shape of the injection rate curve would appear to require advanced unit injectors.[37] At the present time, two of the domestic manufacturers use distributor pump systems and conversion to unit injectors would be a major task. Even for those currently employing unit injectors, such a change would not be minor and could require at least until 1990 to implement. Thus, these changes to the shape of the injection rate may be feasible for some manufacturers and some HDDEs by 1990 but could be quite difficult for others. Again, the reductions projected based on data for this one engine may not be the same as that for another. However, significant reductions in particulate emissions appear achievable with such technology.

c. Reduced Cylinder Heat Rejection

A significant portion of the heat generated by fuel combustion (20-30 percent) is rejected to the engine coolant in order to maintain acceptable temperatures in cylinder walls, heads, and pistons. For a variety of reasons, such as efficiency, size, weight, and wider fuel tolerance, research is being focused on high temperature materials in order to reduce the amount heat rejected to the coolant. This technology appears to have a great potential for affecting emissions as well. Without going into the detail of such "adiabatic" technology, this emission control potential is described below.

Cummins and the Tank Automotive Command (TACOM) have been jointly working on an uncooled HDDE for a number of years. In their latest paper, [38] the emissions of this engine are described. At constant BSFC, NOx emissions decreased 11-15 percent over the 13-mode cycle, which provides results very comparable to the NOx emissions of the transient cycle. Or, put another way, BSFC decreased 1-2 percent at constant NOx emissions.

Particulate was measured via smoke opacity using smoke/particulate correlations developed previously. The results over the three modes tested showed dramatic reductions of 83-86 percent. While some potential error is induced by the use of smoke as a surrogate for particulate, it is relatively certain that the carbonaceous portion of the particulate decreased by this amount, since it is the carbon that causes the opacity. While soluable organic emissions are uncertain, they likely decreased significantly as well, since gaseous HC emissions decreased dramatically.

These results were those for a completely uncooled engine. However, it was noted that the reduction in smoke opacity dropped consistently as the degree of heat retention increased. Therefore, one can expect that the initial stages of heat retention will provide particulate reductions in rough proportion to their degree of heat retention.

The authors present an aggressive timetable for the potential development of this technology. An uncooled engine is projected to be producible by 1987, based in part on the successful demonstration of such an engine in an army 5-ton truck in 1982. Whether this date is for military application alone or for both military and commercial application is unknown. It appears unlikely, however, that such technology would be widely available prior to 1990. For example, EEA only projects its use after 1992 and then only on heavy HDDEs.[24]

Overall, this technology promises very large particulate control potential and in so far that it is available by 1990, large particulate reductions could result.

d. Fuel Modification

It is well known that diesel fuel quality has been deteriorating steadily over the past seven to ten years (eg, lower cetane and higher 90 percent boiling point). Given the continued pressure to obtain as much transportation fuel from a barrel of crude oil as possible, it is unlikely that this trend will reverse itself. Approaches to lowering particulate emissions via improvement of a better quality hydrocarbon fuel appear too expensive for the control obtained. However, the use of a markedly different non-petroleum fuel, methanol, appears to offer large emission reductions, as well as being feasible in HDDEs.

The testing results of three methanol-fueled HDDEs are publicly available: 1) a MAN D2566 FMUH engine[39], a DDA 6V-92TA[25b], and a Volvo TD-100A[39]. The Volvo engine is a dual-fueled engine, using a pilot injection of diesel fuel to ignite the primary methanol fuel. As its emission characterstics are a blend of those expected from use of solely methanol and solely diesel fuel, they will not be discussed here. Instead, this discussion will focus on the two engines operatable on solely methanol, as they reveal most clearly the effect of this fuel.

The emissions and BSFC of these two engines are shown in Table 2-25. As can be seen, the catalyst-equipped MAN engine had extremely low emissions of HC, CO, aldehydes, and particulate. While the presence of an automotive-type catalyst had much to do with the meagerness of the former three pollutants, the particulate emissions were likely low prior to

Table 2-25

Emissions and Fuel Consumption of Two Methanol-Fueled HDDES

	Catalyst-Equipped MAN D2566 FMUH (198 hp)[25g] EPA Transient Test	DDA 6V-92TA (270 hp)[25b] 13-Mode Test
HC (g/BHP-hr)[1]	0.04	1.28
Aldehydes	0.001	0.15
CO (g/BHP-hr)	0.31	--
NOx (g/BHP-hr)	6.61	2.20
Particulate (g/BHP-hr)	0.043	0.17
BSFC (lb/BHP-hr)[2]	0.536	

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[1] Standard HFID measurement.

[2] Diesel equivalent basis using lower heating values.

the catalyst. The BSFC of this engine is roughly 10-15 percent higher than that of typical HDDEs of its type and size (eg., Cat 3208 and DDA 6V-71N).

The DDA engine was tested without a catalyst. While aldehydes were higher than those of a typical HDDE, NOx emissions were extremely low and particulate emissions were below the 0.25 g/BHP-hr standard, but not below the 0.10 level. While the extremely low levels of NOx should allow timing advance to reduce particulate further, there is reason to believe that the 0.17 g/BHP-hr level may be overstated. Only one particulate test was run in a test cell used just prior for diesel testing. Thus, both measurment error and contamination by previously stored diesel particulate could explain the unexpectedly high results. Oil consumption could also explain part of the particulate level, but not all of it. It should be noted that the BSFC of this engine was better than that of its diesel-fueled counterpart, though some advanced features were used on the methanol-fueled engine that are not on the current production 6V-92TA.

Neither of these engines has yet to undergo extensive development for emissions control. Thus, additional reductions are possible . However, both engines appear to be newly ready for production (i.e., two to three years). Both are already being tested by the State of California in in-use transit situations in the San Francisco Bay area. The early indications are that they are fully satisfactory as bus engines.

One problem with the use of methanol that is outside the scope of this analysis is fuel availability. Producing and distributing sufficient quantities of methanol for all HDDEs would be a significant challange. However, for urban HDD fleets and particularly public transit fleets, the purchase and distribution of methanol would be relatively easy due to the use of central fuel depots. Also, the methanol market projection is that excess capacity will be available for sometime to come. Thus, the use of methanol to control HDDE particulate in these situations could easily be realistic for 1990.

3. Summary

The above discussions indicate a large long-term potential to reduce particulate emissions via engine-related means. However, a high degree of uncertainty exists with respect to the applicability of all of these techniques in the 1990 timeframe. Among the more certain effects, NOx controls related to the 1990 standard should not negatively affect circa-1987 particulate levels and may slightly reduce them (i.e., up to 10 percent). Reductions in BSFC caused by general engine improvements should have a definite positive effect on particulate emissions, reducing them by roughly 5-10 percent. Increasing injection pressure showed significant particulate control potential on a Mack engine (25-60 percent), but then whether these reductions would occur on all engines is unknown. However, some degree of particulate reduction potential would appear fairly certain (e.g., 10-15 percent). On the other hand, straight-forward optimization of the combustion chamber appears to hold little promise for substantial particulate control beyond that already considered for 1987. The net effect of these controls should be particulate reductions of roughly 25-35 percent, with higher injection pressures possibly providing greater reductions.

Adiabatic technology promises great particulate reduction potential, upwards of 90 percent. However, its widespread use by 1990 is highly questionable. Highly advanced unit injectors also promise significant potential, but again their availability by 1990 is uncertain. Finally, use of methanol as fuel promises particulate control well below 0.05 g/BHP-hr and appears practical from an engine standpoint for 1990. However, fuel availability is an issue and except for urban fleets, particularly transit bus fleets, is probably not practical for 1990.

Given this, it appears that the largest degree of particulate reduction that can be firmly projected for the entire fleet is roughly 35 percent. Starting with particulate levels complying with a 0.6 g/BHP-hr standard, this roughly translates to levels low enough to meet a 0.4 g/BHP-hr particulate standard. Certainly larger reductions could be feasible for some engines. However, even the 35 percent figure involves a significant degree of uncertainty when the entire HDDE fleet is concerned. Therefore, it does not appear reasonable to project more than a 35 percent reduction for the 1990 timeframe.

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Chapter 3

ECONOMIC IMPACT

This chapter examines the economic impacts of the compliance costs associated with the manufacturers' efforts toward complying with the proposed light-duty truck (LDT) nitrogen oxides (NOx) regulations for 1987 and later model years, the heavy-duty gasoline engine (HDGE) NOx regulations, and the heavy-duty diesel engine (HDDE) NOx and particulate regulations, applicable to the 1987 and 1990 model years. Fixed or pre-production costs (research, development, and testing (RD&T), including certification testing) and variable costs (emission control hardware) will be considered. Certification costs are treated as a one-time fixed cost occurring prior to the first model year in which the standards are applicable, with subsequent model year certification being based on data carryover. The estimates of emission control hardware costs given in this chapter are for the systems expected to be used in complying with the regulations, as described in Chapter 2, Technological Feasibility. Possible changes in operating costs will also be evaluated.

The analysis is divided into two general sections. These sections address costs and socioeconomic impacts. The first section of this chapter identifies the costs to manufacturers and users and is subdivided by vehicle class and regulated pollutant. The socioeconomic section of the analysis addresses the effects of the costs on manufacturers, users, energy, inflation, balance of trade and local and regional effects.

I. Costs

This portion of Chapter 3 presents the analysis of the potential cost impact (in 1984 dollars) of complying with the NOx and particulate emission standards, and will cover research, development and testing costs (fixed costs), emission control hardware costs (variable costs) and operating costs (fuel and maintenance). Work in the areas of RD&T is subject to unforeseen problems and delays which can cause the cost to be higher than originally expected. A 10 percent contingency factor has, therefore, been included throughout this analysis in all estimates of RD&T costs.

A. Light-Duty Trucks (LDTs) - NOx Standard

1. Cost to LDT Manufacturers of NOx Standard

a. Fixed Costs (Research, Development and Testing)

Light-Duty Gasoline Trucks (LDGTs): The proposed LDT NOx emission standards are comparable in stringency to the NOx standard for light-duty vehicles (LDVs). As detailed in Chapter 2 it is reasonable to expect that similar technology will, therefore, be employed, i.e., reduction catalyst and exhaust gas recirculation technologies will predominate. Because similar technology is expected to be used, it is reasonable to expect that there will be little or no need for research. It is inevitable, however, that some design, development and testing costs will be incurred. In the case of exhaust gas recirculation (EGR), costs will be limited to those associated with system recalibrations, because EGR is already applied to all 1984 model year LDGTs.

Design, development and testing work would consist of the tasks to cover: 1) recalibrations of the EGR systems, 2) changes to the exhaust manifold to accommodate the installation of an O_2 sensor, electronic control module installation and wiring harness modifications where closed loop systems are employed for the first time, 3) modifications to the exhaust system to accomodate the new catalyst and necessary changes to the secondary air plumbing, and 4) testing to establish the mechanical integrity of the systems as well as certification testing. The costs for these tasks are estimated to total $19.77 million as detailed below.

Fifty-four LDGT engine families were certified for the 1984 model year with an average of approximately eight system calibrations per family. It is reasonable, however, to expect that there would be fewer EGR calibrations than total system calibrations. Four EGR calibrations per engine family were, therefore, chosen for purposes of this cost analysis. In developing each final EGR calibration it is reasonable that manufacturers will evaluate two calibrations and use the most effective calibration. While some engine families may not require recalibration, the conservative approach used was to assume that all engine families would require this work. The number of engine families and calibrations per engine family was, therefore, assumed to remain constant. The cost for EGR recalibrations will be about $2.85 million based on fifty-four engine families and the evaluation of eight calibrations per engine family, three weeks of effort per calibration, $50 per hour to cover labor, overhead and parts and a ten percent contingency factor.

The second set of tasks cover the redesign of exhaust manifolds and the addition of electronic control modules. The estimates given in Chapter 2 for the catalyst technology mix which will be employed in 1987 were; between 0.7 and 3.7 percent open loop three-way catalyst, between one and ten percent oxidation catalyst and between 86 and 98 percent closed loop three-way catalyst systems. For this cost analysis, the catalyst technology mix will be assumed to be two percent open loop three-way catalysts, five percent oxidation catalysts and 93 percent closed loop three-way catalysts. It was also shown in Chapter 2 that the catalyst technology mix by vehicle sales in 1984 is expected to be about 42 percent three-way catalyst (31 percent closed loop three-way, 11 percent open loop three-way) and 58 percent oxidation catalyst. On an engine family basis, the catalyst technology mix is 43 percent three-way catalysts and 57 percent oxidation catalysts, i.e., essentially the same as that determined on the basis of vehicle sales. Assuming that the present catalyst technology mix carries through 1986, 38 percent of the vehicles will not require the application of new catalyst technology in 1987. Based upon EPA certification records, it is estimated that one-half of the remaining 62 percent can use California specification systems, so that design work, exclusive of exhaust systems, will be required for approximately 31 percent of the vehicles or engine families. With a level of effort of four person-months per family redesign, excluding exhaust system redesign, and $50 per hour to cover personnel, test part procurement and overhead plus a 10 percent contingency factor the cost is approximately $1.23 million.

The cost for the third task, i.e., exhaust system redesign, was developed by identifying the number of exhaust system designs required to accommodate such vehicle differences as wheel base, number of driving wheels, type of transmission and vehicle body configuration (van vs. pick-up for example). For the 1983 model year, 253 probably exhaust system designs were identified. Applying the 31 percent redesign requirement which was previously developed, 4 person-months per redesign and an hourly cost of $50, this cost totals to approximately $3.00 million including a ten percent contingency factor.

The fourth development cost component is the cost to prove the mechanical integrity of the exhaust systems. This cost is approximately $2.59 million based on 60,000 miles of testing at 30 mph average speed, $30 per hour (labor and overhead costs are lower for mileage accumulation than for design) and test cost shared equally with other mechanical durability testing programs plus a ten percent contingency factor.

The final component of the fixed costs is the cost of certification testing. This cost is estimated to be approximately $10.10 million based on the continued production of 54 engine families. The basis for the certification cost estimate per engine family is one durability vehicle operated for 120,000 miles and two data vehicles operated for 4,000 miles each at average speeds of 30 mph with an hourly cost of

$30 for labor, vehicles, fuel, etc. and 28 emission tests per family at a cost of $1,500 each, plus a ten percent contingency factor ($187,000/engine family).

In summary, the total fixed cost of $19.77 million would cover the application and optimization of reducing catalyst technology, exhaust gas recirculation (EGR), and required electronic controls ($9.67 million) plus certification to establish compliance with the standards ($10.1 million).

If it is assumed that these costs are spread over the five model years following introduction of the standards, the initial effort would represent expenditures of approximately $0.74 for design and development and $0.77 for certification per gasoline LDT expected to be produced during those model years (Table 3-1). The sales projections contained in Table 3-1 were derived from references 1, 2, and 3 and from manufacturers comments in response to an NPRM published on January 13, 1982 (Revised Gaseous Emission Regulations for 1984 and Later Model Year Light-Duty Trucks and Heavy-Duty Engines).

Much of the practical application work ($9.67 million) would be accomplished in 1985 with the longer leadtime portions of the Certification testing program being initiated in 1985. The final year, 1986, would involve continued optimization, driveability, fuel economy testing, and completion of the Certification testing. On this basis, the fixed costs are apportioned over the two years which the manufacturers and vendors will have available for development, optimization, and testing according to the following schedule:

	Non-Certification Costs	Certification Costs	Total Fixed Costs for LDGTs
1985	$7.0 million	$ 1.0 million	$ 8.0 million (40%)
1986	$2.67 million	$ 9.1 million	$11.77 million (60%)

Light-Duty Diesel Trucks (LDDTs): As was shown in Chapter 2 (Technological Feasibility), it is expected that EGR will be the technology used on LDDTs in meeting the standards. One manufacturer (GM) is presently using (1984 model year) EGR on its engines and electronic controls are expected to be applied to these engines for compliance with the 1987 NOx standard. As was shown in Chapter 2 these engines account for approximately 60 percent of sales. Design and development costs are estimated to be approximately $38,000. This cost is based on four person months of effort at $50 per hour to cover personnel, overhead, and materials for three calibrations and a ten percent contingency factor. Little effort is expected to be necessary for the development of experimental and production

Table 3-1

Projected Light-Duty Truck and Heavy-Duty Engine Sales (in thousands)*

Light-Duty Trucks

Year	Gasoline	Diesel	Total
1987	2,680	710	3,390
1988	2,670	820	3,490
1989	2,620	940	3,560
1990	2,500	1,040	3,540
1991	2,750	1,100	3,670
Totals	13,040	4,610	17,650

Heavy-Duty Engines

Year	Gasoline	Diesel	Total
1987	385	351	736
1988	382	366	748
1989	382	384	766
1990	371	392	763
1991	367	411	778
1992	364	435	799
Totals	2,251	2,339	4,590

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* Total sales and distribution between gasoline and diesel engines derived from References 1, 2, and 3 and from manufacturers comments in response to NPRM published January 13, 1982 (Revised Gaseous Emission Regulations for 1984 and Later Model Year Light-Duty Trucks and Heavy-Duty Engines).

hardware because the necessary electronic components are already in use on counterpart engines meeting California standards.

Application of EGR to engines which are presently not equipped with this system (approximately 40 percent of sales), can reasonably be expected to incur RD&T costs for redesign of air intake and exhaust manifolds, EGR valve and actuator redesign (assuming that EGR valves already in production for gasoline fueled LDTs form the basis for the design), design of plumbing which will transfer the exhaust gases to the EGR control valve and testing to establish the mechanical durability of the system. The cost for this work per engine family is expected to be approximately $90,000 based on six person months for redesign of the manifolds and the EGR valve and actuator, design of the plumbing plus one-half of the cost of accumulating 60,000 miles for confirming mechanical integrity and a ten percent contingency factor. At present, 24 engine families do not use EGR and one engine family does. The cost for the design and development work for the 24 engine families which are expected to use EGR for the first time is approximately $2.16 million. The total design and development cost is approximately $2.2 million when the GM engine family is included. When spread over the projected total diesel LDT production (Table 3-1) for the five model years following the introduction of the standards the expenditure per vehicle is approximately $0.48. The final component of the pre-production fixed cost is the cost of certification. This cost was estimated to be $187,000 per engine family for gasoline LDTs. The cost for certification for diesel LDTs will be slightly higher than that for gasoline LDTs because of the requirement for measurement of particulate emissions. A reasonable cost per diesel LDT family for certification is, therefore, $200,000. Total costs for certification of 25 diesel engine families is therefore $5.0 million.

Summing the component parts of the fixed costs for LDDTs results in an overall fixed cost of $7.2 million. Using the same overall percentages as were used for LDGTs for allocating the costs between 1985 and 1986 results in the following:

	Non-Certification Costs	Certification Costs	Total Fixed Costs for LDDTs
1985	$2.0 million	$0.9 million	$2.9 million (40%)
1986	$0.2 million	$4.1 million	$4.3 million (60%)

These RD&T costs, together with the RD&T costs for LDGTs, are carried forward and will be combined with the estimated hardware costs to develop the total estimates of manufacturers' costs.

b. Emission Control System Hardware Costs (variable cost)

Light-Duty Gasoline Trucks: As was shown in Chapter 2, it is reasonable to expect that the proposed standards can be met by all LDGTs, but that a variety of emission control strategies could be used based on manufacturer preference and on the emission characteristics of each LDGT family. An estimate of the increase in hardware costs can be developed based on past trends in the application of technology, present technology applications and the technology projections developed in Chapter 2. In developing the cost estimate it is necessary that the overall LDGT application rates for close-loop and open-loop systems be developed as well as the application rates for three-way systems and three-way plus oxidation catalyst systems. In addition to these overall LDGT technology application characteristics, identification of the catalyst size and loading is required. This was done by dividing the LDGTs into three representative engine sizes based on the number of cylinders in the engine. The estimates are developed below.

In the 1982 and 1983 model years, oxidation catalyst technology was used on approximately 85 percent of the light-duty gasoline trucks expected to be sold under Federal emission standards. Non-catalyst and three-way catalyst technologies were used on the remaining 15 percent of the LDGTs. Technology application for LDGTs was distributed approximately as shown in Table 3-2. While not shown in Table 3-2, the ratio between closed-loop three-way-plus-oxidation catalyst and closed-loop three-way catalyst systems was approximately 8:1. Open-loop three-way and three-way-plus-oxidation catalyst systems were essentially not used. The trend for technology application between the 1982 and 1983 model years was away from non-catalyst and oxidation catalyst systems and to three-way catalyst systems (Table 3-2).

In the 1983 model year, the ratio between closed-loop three-way-plus-oxidation catalyst and three-way catalyst technology for light-duty vehicles (LDVs) was approximately 3:2. This ratio is significantly lower than the 8:1 ratio which applied to LDTs in the 1982 and 1983 model years. Because of the generally lower cost of three-way catalysts relative to three-way plus oxidation catalysts, it will be assumed that the 3:2 ratio will be representative of application rates on future LDTs when the LDV and LDT standards will be essentially equal in stringency.

Table 3-2

Light-Duty Trucks, Percent Technology Usage by Model Years for all LDGTs

Model Year	Percent Technology Used No Catalyst	Oxidation Catalyst	Open-Loop 3-way	Closed-Loop 3-Way
1982*	4.2	91.2	0.2	4.4
1983*	1.4	80.3	0	18.3
1984*	0	58.0	11.0	31.0
1985 & 1986 (projected)**	0	58.0	11.0	31.0
1987 and later (projected)	0	5.0	2.0	93.0

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* Based on data provided by manufacturers as part of the certification procedure.

** If the increase in the usage of three-way systems which occurred between the 1982 model year and the 1984 model year were to continue to the 1986 model year, the projected catalyst technology utilization rate in the 1986 model year would be about 22 percent oxidation catalyst, 20 percent open-loop three-way and 58 percent closed-loop three-way.

Beginning with the 1984 model year, the stringency of the hydrocarbon (HC) and carbon monoxide (CO) standards for LDTs was increased without any change in the NOx standards. As was shown in Chapter 2 information provided by manufacturers for the purpose of 1984 model year certification shows that the sales split by technology is expected to be approximately 31 percent closed-loop three-way, 11 percent open-loop three-way and 58 percent oxidation catalyst. These sales splits by technology are presented in Table 3-2. It should be noted that the trend away from oxidation catalyst systems which occurred in the 1982 and 1983 model years has carried on into the 1984 model year. Because of the lower cost of oxidation catalyst systems relative to three-way systems, it is reasonable to expect that oxidation catalyst systems will continue to predominate until the 1987 model year.*

In summary, it is likely that the technology application rates in the 1986 model year LDGT fleet will be approximately as follows: 58 percent oxidation catalyst, 11 percent open-loop three-way catalyst, 20 percent closed-loop three-way plus oxidation catalyst and 11 percent closed-loop three-way catalyst. These percentages form the starting point from which the hardware cost increase will be calculated.

The previously developed estimate (Chapter 2) of the catalyst technology mix for 1987 did not distinguish between three-way plus oxidation catalyst systems and three-way systems. Applying the 3:2 ratio for these technologies results in an overall technology mix in 1987 of 5 percent oxidation catalyst, two percent open-loop three-way catalyst, 56 percent closed-loop three-way plus oxidation catalyst and 37 percent closed-loop three-way catalyst. As was noted previously, 38 percent of the LDGTs will not be changed between 1986 and 1987. Changes in catalyst technology would be apportioned as follows: 36 percent would be converted from oxidation catalyst systems to closed-loop three-way plus oxidation catalyst systems, 17 percent would be converted from oxidation catalyst to closed-loop three-way catalyst systems and nine percent would be converted from open-loop to closed-loop three-way catalyst systems. These percentile changes in technology application on a fleet-wide basis are converted to a fleet cost through the development of technology cost estimates for different size engines and estimates of sales by engine size.

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* If the increase in the usage of three-way technology which occurred between the 1982 model year and the 1984 model year were to continue to the 1986 model year, the projected catalyst technology utilization rate in the 1986 model year would be about 22 percent oxidation catalyst, 20 percent open-loop three-way and 58 percent closed-loop three-way.

In preparing the estimate, LDGTs were divided into subclasses based on the number of cylinders in the engine. Use of these subclasses permits development of representative engine sizes for each subclass and the subsequent development of the costs of the catalysts which are expected to be employed. Certification records for the 1980-84 model years formed the basis for the follwing size versus number of cylinder groups. In the case of 4-cylinder engines, the displacements ranged between 1.8 and 2.4 liters with the majority being in the 2.3 to 2.4-liter size. A representative size of 145 cu.in. (2.375 liter) was chosen. The representative size for 6-cylinder engines which was selected to cover their range of 2.8 to 4.9 liters was 240 cubic inches (3.9 liter). Eight-cylinder engines were 5 liters and larger and the representative size selected was 325 cubic inches (5.3 liter).

Turning to the issue of future sales splits, it is expected that a general downsizing of LDTs will occur over the next several years, due primarily to fuel economy pressures, with emissions as a secondary consideration. In addition to the introduction of more fuel efficient truck lines with smaller engines, domestic manufacturers can be expected to adjust their sales mixes such that they sell fewer of their large CID engines, and more of the smaller, more fuel efficient engines. The 1980, 1982, 1983, and 1984 sales projection data submitted by the manufacturers for certification, broken into the three cylinder and CID groups, is shown below. The shift from 8-cylinder to 4-cylinder and 6-cylinder engines is expected to continue and was used in developing the 1987-91 sales projections shown below.

Sales Splits - Gasoline Engines

		Approximate Market Percentages				
		Manufacturer-Furnished Data				EPA Market Projection
Number of Cylinders	Engine CID Range	1980	1982	1983	1984	(1987-91)
4	under 170	11%	22%	41%	30%	40%
6	170-300	19%	44%	34%	42%	40%
8	over 300	70%	34%	25%	28%	20%

The past, present and projected technology applications by engine size are shown in Table 3-3. The application rates by engine size for the 1982 through 1984 model years are based on manufacturer provided sales projections. The EPA projections for 1986 are based on the 1982 through 1984 model year trends and the assumption that technology application rates will be stable from the 1984 through 1986 model years. Projections for

Table 3-3

Light-Duty Trucks, Percent Technology Usage in Model Years by Number of Cylinders for Gasoline-Fueled Vehicles*

	Percent Technology Used				
			Open Loop	Closed Loop	
	No Cat	Ox Cat	3-Way	3-Way	3-Way + Ox
4 Cylinder					
1982MY	8.7	87.6	1.0	2.7	0
1983MY	0	74.9	0	1.5	23.6
1984MY	0	74.5	1.2	1.4	22.9
1986MY, Projected	0	75	1	1	23
87+MY, Projected	0	5	1	37	57
6 Cylinder					
1982MY	0	92.5	0	3.3	4.2
1983MY	4.2	86.3	0	8.7	0.8
1984MY	0	49.5	0	20.2	30.3
1986MY, Projected	0	50	0	20	30
87+MY, Projected	0	5	0	38	57
8 Cylinder					
1982MY	6.7	91.8	0	0	1.5
1983MY	0	80.9	0	0	19.1
1984MY	0	54.5	39.5	0	6.0
1986MY, Projected	0	55	30	0	15
87+MY, Projected	0	5	8	35	52
Fleet Average					
1987, Projected	0	5	2	37	56

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* Percentages for 1982 through 1984 model years derived from data provided by manufacturers as part of the Certification procedure.

1987 were based on the overall fleet technology rates as developed in Chapter 2 and the trends for each size of engine for the years 1982 through 1986. In the case of oxidation catalysts it was assumed that the five percent overall fleet application rate would be achieved by an equal application rate of five percent on each engine size class. For the open loop three-way systems it was assumed that the one percent application rate for 4-cylinder engines would continue and that these systems would not be introduced on 6-cylinder engines as indicated by the previous trend. Achieving an overall fleet average installation rate of two percent necessitated, therefore, that eight percent of the 8-cylinder engines use open loop three-way systems in 1987. For the closed loop systems, the percentile splits between three-way and three-way-plus-oxidation catalyst systems were derived on the basis of the overall fleet installation rates, the sales distribution between the three engine cylinder groups and the previously identified 3:2 ratio between three-way-plus-oxidation catalyst systems and three-way systems.

On the basis of the sales and technology rate projections for the 1986 and 1987 model years fleets, conversions from oxidation catalysts to closed-loop three-way or closed-loop three-way-plus-oxidation catalyst will involve 70 percent of the 4-cylinder LDGTs, 45 percent of the 6-cylinder LDGTs, and 50 percent of the 8-cylinder LDGTs. Conversions from open-loop to closed-loop three-way systems will involve 22 percent of the 8 cylinder LDGTs. Applying the 3:2 ratio previously identified for closed-loop three-way plus oxidation catalyst to closed-loop three-way catalyst usage results in the application rates for these technologies as shown in Table 3-3. These percentages, coupled with the costs for each technology, will permit the development of an average cost once the cost differentials for 4-, 6-, and 8-cylinder LDTs are estimated.

Certification records for the 1983 and 1984 model years were used to develop estimates of catalyst size as a function of engine size as well as estimates of catalyst loading as a function of catalyst type. This information was used in conjunction with the cost estimation procedures given in Reference 4 to develop the catalyst cost estimates shown in Tables 3-4 through 3-6.

Tables 3-4, 3-5, and 3-6 show the estimated increase in hardware costs for each configuration applicable to 4-, 6-, or 8-cylinder engines. The credits taken are for the emission control system which are expected to be used to comply with the emission standards through the 1986 model year. As can be seen in Tables 3-4 through 3-6, the hardware cost estimates range from a low of $65 for 8-cylinder engines where closed-loop

Table 3-4

Light-Duty Gasoline Truck, Emission Control System Cost, 4-Cylinder 145-CID Engines[4,5]*

	Hardware Added				Hardware Removed				
Configuration	Three-Way Catalyst	Three-Way-Plus-Oxidation Catalyst	Feedback Carburetor Modifications	Closed-Loop Control	Oxidation Catalyst	Air Injection	EGR	Open-Loop Control	Total
1	$111	-	$11	$126	$70	-	-	$72	$106
2	-	$134	$11	$126	$70	-	-	$72	$129

---

* Cost Estimates developed from Reference 1 and account for inflation using new car price inflation indices provided by the Bureau of Labor statistics for 1978, 1979, 1980, 1981, 1982, and 1983 of 6.2 percent, 7.4 percent, 7.5 percent, 6.8 percent, 1.6 percent and approximately 3.6 percent respectively.

Table 3-5

Light-Duty Gasoline Truck, Emission Control System Cost, 6-Cylinder 240 CID Engines[4,5]*

	Hardware Added				Hardware Removed				
Configuration	Three-Way Catalyst	Three-Way-Plus-Oxidation Catalyst	Feedback Carburetor Modifications	Closed-Loop Control	Oxidation Catalyst	Air Injection	EGR	Open-Loop Control	Total
1	$169	-	$11	$126	$101	-	-	$72	$133
2	-	$216	$11	$126	$101	-	-	$72	$180

---

* Cost Estimates developed from Reference 1 and account for inflation using new car price inflation indices provided by the Bureau of Labor statistics for 1978, 1979, 1980, 1981, 1982, and 1983 of 6.2 percent, 7.4 percent, 7.5 percent, 6.8 percent, 1.6 percent, and approximately 3.6 percent respectively.

Table 3-6

Light-Duty Gasoline Truck, Emission Control System Cost, 8-Cylinder 325 CID Engines[4,5]*

	Hardware Added				Hardware Removed				
Configuration	Three-Way Catalyst	Three-Way-Plus-Oxidation Catalyst	Feedback Carburetor Modifications	Closed-Loop Control	Oxidation Catalyst	Air Injection	EGR	Open-Loop Control	Total
1	$221	-	$11	$126	$129	-	-	$72	$157
2	-	$289	$11	$126	$129	-	-	$72	$225
3	-	-	$11	$126	-	-	-	$72	$65

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* Cost Estimates developed from Reference 1 and account for inflation using new car price inflation indices provided by the Bureau of Labor statistics for 1978, 1979, 1980, 1981, 1982, and 1983 of 6.2 percent, 7.4 percent, 7.5 percent, 6.8 percent, 1.6 percent, and approximately 3.6 percent respectively.

three-way catalyst systems replace open-loop three-way catalyst systems to $225 for 8-cylinder engines where oxidation catalysts are replaced by closed-loop three-way plus oxidation catalyst systems.

Combining the hardware costs and sales projections which have just been developed permits the development of an average hardware cost for LDGTs as follows:

° Forty percent of sales will be 4-cylinder engines. Of this total, 70 percent will utilize new technology with 36 percent being converted to closed-loop three-way catalyst systems and 34 percent being converted to closed-lop three-way plus oxidation catalyst systems. The average hardware cost increase for a 4-cylinder truck which receives new catalyst technology is, therefore, [($106 x 0.36) + ($129 x 0.34)]/0.70 = $117.17. The contribution by 4-cylinder LDGTs to the average hardware cost for all LDGTs is:

  0.4 x 0.7 x $117.17 = $32.81.

° In the case of 6-cylinder engines, 45 percent will use new technology with 18 percent receiving closed-loop three-way systems and 27 percent receiving closed-loop three-way plus oxidation catalyst systems. The average hardware cost increase for the new systems will be: [($133 x 0.18) + ($180 x 0.27)]/0.45 = $161.20. With 6-cylinder sales representing 40 percent of total sales, the contribution by 6-cylinder LDGTs to the average hardware cost for all LDGTs is:

  0.4 x 0.45 x $161.20 = $29.02

° Eight-cylinder engines represent 20 percent of sales, with 50 percent of the 8-cylinder engines being changed from oxidation catalyst technology to closed-loop systems. An additional 22 percent will be changed from open-loop to closed-loop three-way systems. The average hardware cost increase for new systems on 8-cylinder trucks will, therefore, be: [($157 x 0.13) + ($225 x 0.37) + ($65 x 0.22)]/0.72 = $163.83. The contribution by 8-cylinder engines to the average hardware cost of the LDGT fleet is:

  0.20 x 0.72 x $163.83 = $23.59

- The average hardware cost per LDGT in the fleet is the sum of the contributions by the three groups of engines and is:

  $32.81 + $29.02 + $23.59 = $85.42 or approximately $85*

These costs will be carried forward in developing estimates of the average hardware costs for all LDTs.

The average hardware cost for LDGTs which require new hardware is calculated using the same procedure as was employed above but without distributing the cost over those vehicles which do not require new technology. This cost is $137.77 or approximately $138.

Light-Duty Diesel Trucks: The hardware cost for LDDTs would come from the application of non-electronically controlled EGR to 40 percent of the vehicles and the conversion of 60 percent of the vehicles to electronically controlled EGR. The estimated cost of the EGR system which is expected to be added to LDDTs not previously equipped with EGR is $20.[4] The hardware cost for the addition of electronic controls is estimated using the system design employed by GM on their engines designed to comply with the California standard. In Reference 1, EPA estimated the cost of an electronic control module for use on LDDTs as being $19. The cost of a pressure sensor for determining particulate trap backpressure was estimated as being $2. These costs will be used as the basis for the estimate of the cost for electronic controls for LDDT EGR systems. Sensors which will be employed as part of the electronic EGR control system are expected to monitor engine speed, load, and absolute pressure. The load sensor (throttle position) is expected to be a proportional unit replacing an on/off unit used on the non-electronic systems. The incremental cost can be expected, therefore, to be about $3. The engine speed sensor will be required to deliver a proportional signal and can be an electrical pulse generator. The cost is estimated to be $3. The cost of the absolute pressure sensor is estimated to be $10 for an aneroid and the electrical position signal generator. The final major component of the electronic control system is the actuator which will modulate the EGR valve as directed by the control module. On the California specification engines, GM controls the EGR flow by the use of a pulsed solenoid. The cost for this component is estimated to be $5. The remainder of the system consists of electrical connectors, a filter, and small vacuum liner. The cost of these components is estimated to be $2. Summing the costs of the component parts of the elctronic control system gives the estimate of the cost of the total system as follows:

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* A hardware cost of $42, developed as follows, could be projected if the trend in the use of three-way technology which occurred between the 1982 model year and the 1984 model year were to continue to the 1986 model year:

Hardware Cost = Seventeen percent of LDTs are changed from oxidation to closed-loop three-way catalyst at an average cost of $178 per vehicle ($129 + $180 + $225)/3 plus 18 percent of LDTs are changed from open-loop to closed-loop systems at a cost of $65 per vehicle.

> $19 for the control module + 1 sensor at an incremental cost of $3 + 2 sensors at a total cost of $13 + $2 for the connectors, etc. + $5 for the actuator for a total of $42.

Combining the cost estimates and the sales split between the first time application of EGR and the conversion to electronic EGR systems results in an average hardware cost for LDDTs of:

> 0.60($42) + 0.40($20) = $33.20, or approximately $33

These costs will be carried forward to develop estimates of the hardware cost for all LDTs.

LDT Fleetwide Average Emission Control Hardware Costs: Having estimated control system costs for gasoline and diesel-powered LDTs, all that remains is to determine the fleetwide average cost. As shown in Table 3-1, sales of LDTs in the 5-year period, 1987-91, are expected to consist of 13,040,000 gasoline-powered vehicles and 4,610,000 diesel-powered vehicles. Gasoline-powered vehicles are expected, therefore, to represent 73.9 percent of sales and diesel-powered vehicles to represent 26.1 percent of sales. Weighting the average hardware costs for gasoline-powered vehicles ($85.42) and diesel-powered vehicles ($33.20) by their respective sales fractions results in an average hardware cost for all LDTs of approximately $72 as shown below:

> 0.261 ($33.20) + 0.739 ($85.42) = $71.79 or approximately $72

c. Total Costs to Manufacturers

The major costs to manufacturers of RD&T and emission control hardware are summarized in Table 3-7. The costs presented are shown in the year in which they are expected to occur, and include profit and overhead. The total undiscounted cost, $1.29 billion shown in Table 3-7, should provide sufficient funds to comply with all aspects of this proposed rulemaking action. The discounted value ($1.08 billion) is shown in Table 3-8. The costs are also shown in Tables 3-9

Table 3-7

Light-Duty Trucks, Total Cost (undiscounted) to Manufacturers of LDTs Manufactured in 1987-91 Model Years

Year	RD&T	Emissions Hardware
1985	$10.90M	-
1986	16.07M	-
1987	-	$243.37M
1988	-	250.55M
1989	-	255.57M
1990	-	254.14M
1991	-	263.47M
	$26.97M	$1,267.10M

Total undiscounted cost: $1,294.07M (1984 dollars)

Table 3-8

Light-Duty Trucks,
Present Value in 1987 of the
Costs of Compliance for the 1987-91 Model Years

Capital and Emission Control Systems:

Year[1]	Cost[2]	Present Value in 1987[3]
1985	$ 10,900K	$ 13,190K
1986	16,070K	17,680K
1987	243,370K	243,370K
1988	250,550K	227,770K
1989	255,570K	211,215K
1990	254,140K	190,940K
1991	263,470K	179,955K
Total:	$1,294,070K	$1,084,120K

Operating Costs for Fuel:

Change in cost per 1 percent change in fuel economy		±$855,592K

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[1] Costs are assumed to occur at the start of each year and are allocated according to Table 3-7.

[2] 1984 dollars, including profit and overhead.

[3] 10 percent discount rate.

Table 3-9

Light-Duty Trucks, Aggregate Costs of Compliance for LDTs Produced During Model Years 1987-91 (discounted at 10% to January 1, 1987)

Development and Testing	$30,870K
Emission Control Systems	1,053,250K
	$1,084,120K
Operating Costs	
Change in aggregate cost per one percent change in fleetwide fuel economy	±$855.6M

through 3-12 expressed as discounted total costs for RD&T and hardware, discounted and undiscounted costs per vehicle and as RD&T costs per fuel type.

2. Cost to Users (LDT-NOx)

a. Increases in First Costs

The added cost to manufacturers for RD&T and emission control system hardware is expected to be passed on to the purchasers of LDTs. The amount a manufacturer must increase the price of its vehicles to recover its expenses depends on the timing of the costs, the revenues from sales, and on the cost of capital to the manufacturer. Table 3-7 showed the manner in which the manufacturers' costs are distributed over the period 1985-91. It is expected that manufacturers face a 10 percent cost of capital over the long run, and that they increase the vehicle prices to recover their pre-production investment in five model years, 1987-91. The first price increase of a vehicle would be the sum of the discounted RD&T costs allocated on a per vehicle basis plus the cost of the hardware.

The first price increase for LDTs in 1987 is shown in Table 3-13 in terms of vehicles which employ new technology and as average price increases. The expected sales-weighted average first price increase for LDTs requiring the application of new technology is approximately $140 for LDGTs and $35 for LDDTs. The sales weighted average price increase for all LDTs is approximately $74. The first price increase for LDTs using new technology would consist of development costs (discounted) plus hardware costs and would range in the case of gasoline-powered LDTs from a low of approximately $67 for 8-cylinder LDGTs which are converted from open-loop to closed-loop three-way catalyst systems, to a high of $227 for 8-cylinder LDGTs which are converted from oxidation catalyst systems to three-way-plus-oxidation catalyst systems. LDDTs are expected to increase in price by an average of $35.

b. Fuel Economy

As was shown in Chapter 2, it is reasonable to expect that some small increase could occur in the fuel economy of some LDGTs and some small decrease could occur in the fuel economy of some LDDTs. The potential fuel economy improvements on LDGTs could be available in a couple of areas. The first area of potential savings is related to the use of electronic engine controls and feedback carburetors (closed-loop systems). These components would allow the air/fuel ratio to be maintained nearer to stoichiometric conditions, and would allow better use

Table 3-10

Light-Duty Trucks,
Undiscounted Cost of Compliance per LDT
when Distributed Over All LDTs Produced During 1987-91

Development and Testing ($1.51 for LDGT, $1.56 for LDDT)	$ 1.52
Emission Control Hardware (sales-weighted average)	72.00
Undiscounted Cost per Vehicle	$73.52
Operating Cost	
Change in operating cost per one percent change in fuel economy (non-discounted)	±$ 74.63

Table 3-11

Light-Duty Trucks, Discounted Cost of Compliance per LDT[1] for LDTs Produced During 1987-91

Development and Testing ($1.74 for LDGT, $1.79 for LDDT)	$ 1.75
Emission Control Hardware (sales weighted average)	59.67
Discounted Cost Per Vehicle	$61.42
Operating Cost	
Change in operating cost per one percent change in fuel economy	± $48.48

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[1] Discounted to 1987 at 10 percent.

Table 3-12

Light-Duty Trucks, Pre-1987 RD&T Costs
(1984 dollars undiscounted)

LDGT	$ 19,770K
LDDT	7,200K
Vendor:	
Gasoline-powered LDT: (tooling and equipment for catalytic converters, closed loop electronic controls, and other emission-related hardware)	126,390K
	$153,360K

Table 3-13

Light-Duty Trucks, First Price Increases for Trucks with New Technology and Sales Weighted Averages (1984 dollars)

4 Cylinder Closed-Loop Three-Way Catalyst from Oxidation Catalyst	$108
4 Cylinder Closed-Loop Three-Way Plus Oxidation Catalyst from Oxidation Catalyst	131
6 Cylinder Closed-Loop Three-Way Catalyst from Oxidation Catalyst	135
6 Cylinder Closed-Loop Three-Way-Plus-Oxidation-Catalyst from Oxidation Catalyst	182
8 Cylinder from Open-Loop to Closed-Loop Three-Way Catalyst	67
8 Cylinder Closed-Loop Three-Way Catalyst from Oxidation Catalyst	159
8 Cylinder Closed-Loop Three-Way-Plus-Oxidation Catalyst from Oxidation Catalyst	227
Light-Duty Diesel Trucks	35
Sales-Weighted Average price increase for LDGTs requiring new technology is approximately	140
Sales-Weighted Average price increase for all LDGTs is approximately	87*
Sales-Weighted Average price increase for LDDTs requiring new technology is approximately	35
Sales-Weighted Average price increase for all LDTs is approximately	74**

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* $44 if the trend in the use of three-way technology which occurred between the 1982 model year and the 1984 model year were to continue to the 1986 model year.

** $42 if the trend in the use of three-way technology which occurred between the 1982 model year and the 1984 model year were to continue to the 1986 model year.

of the energy available in the fuel. A second potential fuel economy improvement lies in the substitution of "pulse air" air injection for air pump supplied air injection in some LDGTs. The fuel savings attributable to these changes could be in the two percent to four percent range (Chapter 2). It is very difficult, however, to estimate the number of vehicles which could be involved in these savings because manufacturers will have to evaluate each engine family on the basis of its emission characteristics. While the fuel economy changes which may occur cannot be quantified precisely at this time, a fuel economy improvement of 1 percent for all gasoline-powered LDTs would mean a lifetime reduction in operating costs of approximately $51 (20 mpg base, 120,000 miles in 11 years, $1.30/gal, 10 percent discount rate).

In the case of LDDTs some vehicles may incur a small fuel economy penalty as a result of these regulations. As was shown in Chapter 2, the effect is not expected to be measurable on small LDDTs and in the case of large LDDTs the effect is expected to be less than one percent. It is possible, however that any fuel economy penalty attributable to increased EGR rates may be avoided by the use of electronically controlled EGR systems. For LDDTs, a 1 percent change in fuel economy means a $41 (23 mpg base, 120,000 miles in 11 years, $1.20/gal, 10 percent discount rate) change in lifetime operating costs.

c. Maintenance

Changes in the costs of maintenance attributable to the NOx standard for LDTs, are not expected to occur. User costs in this area are, therefore, not expected to change.

d. Total Costs to Users

To summarize, it is reasonable to expect that users of LDTs can expect to pay an average of about $74 more for 1987 model year LDTs than for comparable models purchased in 1986 (1984 dollars). Operating costs of LDDTs could increase as a result of these regulations if losses in fuel economy occur. Conversely, operating costs of gasoline-powered LDTs may decrease as a result of improvements in fuel economy.

3. Aggregate Costs (LDT NOx)

The aggregate cost to the nation of complying with the proposed 1987 Federal LDT NOx emission regulations consists of the sum of fixed costs for RD&T and new emission control hardware. These costs are calculated based on sales projections for the 5-year period following introduction of the standard.

The 5-year costs of compliance are dependent on the number of LDTs sold during the period. The accuracy and validity of projecting vehicle sales as far into the future as 1991 is problematic, so cost estimates based on such projections are subject to some qualification. However, because the largest portion of the costs in this analysis are variable costs (hardware), and not fixed costs (RD&T), the accuracy of the sales projections are not as critical as might be the case in some other rulemaking actions. Future sales of LDTs for the analysis period were discussed previously, and were shown in Table 3-1.

The various costs associated with this rulemaking action will occur in different periods. In order to make all costs comparable, the present value at the start of 1987 of the aggregate costs has been calculated, based on a discount rate of 10 percent. The calculations and the assumptions required for the calculations, are shown in Table 3-8. The aggregate cost of complying with the new regulations for the 5-year period is estimated to be equivalent to a lump sum investment of about $1.08 billion (1984 dollars), made at the start of 1987. Expressed in other terms, the aggregate cost of compliance is equivalent to an investment of $61 per LDT, made at the start of the year these NOx standards become effective. The aggregate cost changes by about $856 million for each 1 percent change in LDT fuel economy.

For ease of reference, the components of the cost of compliance and the different methods of expressing it are summarized in Tables 3-9 through 3-12.

B. Heavy-Duty Gasoline Engines (HDGEs) - NOx Standards

1. Cost to HDGE Manufacturers of the NOx Standards

a. Fixed Costs (Research, Development and Testing)

The technologies which can be expected to be required on HDGEs to meet the 1987 and 1990 NOx standards were identified in Chapter 2. That analysis showed that HDGEs can be expected to be brought into compliance with the 1987 standard through recalibrations of the fuel, ignition, and EGR systems. For the 1990 standard, combustion chamber redesign for the application of "fast-burn" technology coupled with the development of appropriate calibrations for the fuel, ignition and EGR systems were the most probable approaches which manufacturers are expected to employ. Other technologies which were identified, but which were judged not to be required for compliance with the 1990 standard were: electronic controls, fuel injection, and three-way catalysts. For this analysis, it was assumed that manufacturers would use "fast-burn" combustion chambers which employ a single spark plug and that, as a consequence, substantial ignition system redesign would be avoided.

Development and testing costs are not expected to be large for the recalibration of the fuel, ignition, and EGR systems. Because essentially similar work is expected to be required for the recalibrations for the 1987 standard and for the 1990 standard, a single calculation will be performed to develop the recalibration costs. This cost will then be applied to both the 1987 and the 1990 standards. Similarly, the costs of certification will be calculated once and the applicable* cost will be applied to each of the standards. As a first estimate, the costs of the calibrations and the certification testing, per engine family, are estimated as follows:

- Development of three calibration combinations of EGR, fuel and ignition systems per engine family with the optimum calibration selected for production. Six person weeks of effort per calibration at $50 per hour results in a cost of $36,000.

- Certification testing involving one durability and three data engines per engine family. Dynamometer operation time of 3,500 hours** for the durability engine, and 130 hours per emission-data engine at a cost of $30 per hour results in a cost of $116,700.

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* New split-class standards for HC and CO are effective beginning with the 1987 model year. The new, more stringent statutory standards will apply to 70 percent of the HDGEs while the 1985 standards would remain in effect for the remaining 30 percent. As a result, 70 percent of the HDGEs will require certification testing to establish compliance with the HC and CO standards and 30 percent will utilize carryover HC and CO certification. Additional costs for certification testing for the 1987 NOx standard would, therefore, not be required for 70 percent of the HDGEs. The cost allocated in this action for certification testing associated with the 1987 model year NOx standard is, therefore, limited to 30 percent of the HDGEs.

** Prior to the 1984 model year, 1,500 hours of dynamometer operation of a HDGE was used to represent 50,000 miles of vehicle operation. Direct proportioning of these values to a lifetime mileage of 110,000 miles would result in a dynamometer operating time requirement of 3,300 hours. To be conservative, EPA increased the 3,300-hour value by a contingency factor of approximately six percent to arrive at the value of 3,500 hours which is used in the cost estimate. Present regulations require durability data engines to be operated in such a fashion as to represent real-world conditions but allow manufacturers to select the operating conditions. It is possible, therefore, that manufacturers may identify procedures which would allow some reduction in the dynamometer-hour requirements for durability engines. Under these conditions, the cost of collecting data on durability engines could be reduced.

- Emission tests at 150-hour intervals for the durability engine for a total of 23 tests and two tests per data engine at a cost of $2,000 per test results in a cost of $58,000.

Application of a 10 percent contingency factor results in a total cost per engine family of approximately $232,000 for recalibrations and certification. These are the only fixed costs which apply to the 1987 standard. In addition to the recalibration and certification costs, the fixed costs for the 1990 standard would include work necessary to redesign the combustion chamber. For HDGEs, combustion chamber redesign is expected to be achieved through a redesign of the cylinder head. This task would involve the design effort, prototype part procurement, testing to establish the performance of the design, mechanical durability testing, and necessary design modifications to incorporate the results of the testing programs. As a first estimate, two person-years of effort will be assigned for the design, performance testing, and any necessary redesigns. At an hourly cost of $50, including the cost of prototype parts, this effort comes to $208,700 per engine family. Dynamometer test time to prove mechanical durability will be assumed to cover full engine life (110,000-mile equivalent) and is assumed to be performed under higher than average mechanical and thermal load conditions. These conditions are assumed to be reflected in engine speeds which correspond to a vehicle speed which is 50 percent higher than that used for certification testing, i.e., at 45 mph equivalent. These assumptions lead to a mechanical durability dynamometer test time of 2,333 hours and a corresponding cost of $70,000. The fixed cost per engine family for the cylinder head redesign is, therefore, estimated to be approximately $279,000. The total fixed cost per engine family for the 1990 standard is the sum of the component parts of the fixed cost and is approximately $539,000, including a 10 percent contingency factor.

Being conservative, it is possible that there could be as many as 22 heavy-duty gasoline engine families in production in the 1987 and later model years (assuming that each of the 11 existing basic engine groups are divided into two engine families). The total fixed or pre-production cost for each of the NOx standards would, therefore, be $1.5 million ($232,000 X 22 X 0.3) for the 1987 standard and $11.9 million ($539,000 X 22) for the 1990 standard (Table 3-14). Expressed on a per-engine basis for engines produced in the model years 1987-89 and 1990-92 covered by the NOx standards (Table 3-1),

Table 3-14

Heavy-Duty Gasoline
Engines; Costs and Present Values* of
Complying with the 1987 and 1990 NOx Standards (1984 dollars)

Year	Cost Fixed	 Hardware	Present Value In 1987	Present Value In 1990
1985	$766K	--	$927K	--
1986	766K	--	823K	--
1987	--	--	--	--
1988	8,000K	--	--	9,680K
1989	3,858K	--	--	4,244K
1990	--	1,855K	--	1,855K
1991	--	1,835K	--	1,668K
1992	--	1,820K	--	1,504K
TOTAL	$13,390K	$5,510K	$1,750K	$18,951K

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* 10 percent discount rate to year standard is introduced.

this cost is $1.33 for the 1987 standard and $10.76 for the 1990 standard (Table 3-15). These costs are expected to be spread over the two years preceding the introduction of the 1987 and 1990 model year engines (i.e., during 1985 and 1986 for the 1987 standards and during 1988 and 1989 for the 1990 standards). Distribution of the costs between the years can reasonably be expected to be as shown in Table 3-14.

b. Emission Control Systems Hardware Costs (Variable Costs)

For the 1987 standard, it is probable that manufacturers of gasoline-fueled HDEs will recalibrate existing systems and will, therefore, not incur any significant hardware costs.

For the 1990 standard, hardware costs will probably be mainly attributable to the new cylinder heads. While it could be assumed that the redesigned cylinder heads would not cost any more than those which are being replaced, a conservative approach was used and a cost increase of $5 per engine was assigned. For the engines which are expected to be produced, this per engine cost of $5 represents totals of $1,855,000 in 1990, $1,835,000 in 1991, and $1,820,000 in 1992 (Table 3-14). If manufacturers choose to use one or more of the other technologies which were identified in Chapter 2, the costs can reasonably be expected to increase appropriately.

c. Total Costs to Manufacturers

The total cost to HDGE manufacturers of complying with the 1987 NOx standards is estimated to be approximately $1.5 million coming exclusively from fixed costs. For the 1990 NOx standard, both fixed and variable costs are involved and total approximately $17.4 million. On a per-vehicle basis, the total cost is estimated to be $1.33 for the 1987 standard and $15.76 for the 1990 standard (Table 3-15). The discounted costs per engine are shown in Table 3-16 and are $1.52 for the 1987 standard and $17.20 for the 1990 standard.

2. Costs to Users (HDGE - NOx)

a. Increase in First Cost

For the 1987 standard, the first price increase will consist only of the discounted-fixed costs of $1.52 or approximately $2. For the 1990 standard, the first price increase will consist of the discounted fixed cost ($12.64) plus the hardware cost ($5.00) for a total of $17.64 or approximately $18.

Table 3-15

Heavy-Duty Gasoline Engines, Undiscounted Costs of Compliance with the Standards per Engine for Engines Produced in 1987-89 and 1990-92

Manufacturer Cost	1987-89	1990-92
Research, Development & Testing	$1.33	$10.76
Emission Control Hardware	--	5.00
	$1.33	$15.76
Operating Cost		
Change in Fuel Cost per one Percent Change in Fuel Economy	$143	$143

Table 3-16

Heavy-Duty Gasoline Engines, Discounted
Costs of Compliance per Engine for
Engines Produced in 1987-89 and 1990-92*

Manufacturer Cost	1987-89	1990-92
Research, Development & Testing	$1.52	$12.64
Emission Control Hardware	--	4.56
	$1.52	$17.20
Operating Cost		
Change in Fuel Cost per one Percent Change in Fuel Economy	$104.92	$104.92

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* 10 percent discount rate to year standard is introduced.

b. Fuel Economy

While changes in the calibrations of fuel, ignition, and EGR systems can have some impact on fuel economy, it is expected that the system recalibrations should not result in any fuel economy penalty. In fact, other measures to improve fuel economy will probably be taken in this period because of market pressure in that direction.

While a fuel economy effect is not anticipated, an estimate has been prepared of the cost of a fuel economy change for purposes of completeness in this document. This value was computed by using a fuel cost of $1.30 per gallon, a fleet average fuel economy of 10 miles per gallon, a 110,000 mile/8-year lifetime, and a 10 percent discount rate. These computations show that each 1 percent change in fuel economy yields a $105 discounted change in operating costs for fuel over the lifetime of the engine (Table 3-16).

c. Maintenance

The cost of maintenance is not expected to be impacted by either the 1987 model year or the 1990 model year NOx standards for HDGEs.

d. Total Costs to Users

To summarize, owners of gasoline-fueled HDVs can, as a result of the proposed NOx standards, expect an increase in first price of approximately $2 in 1987 and $18 in 1990 with no change in operating cost.

3. Aggregate Costs

For HDGEs, the aggregate cost to the nation of compliance with the 1987 and the 1990 NOx standards would consist of the fixed costs and the hardware costs discounted to the years in which the standards become effective. As in the case of LDTs, a 10 percent cost for capital is employed in determining the lump sum investment which would be equivalent to the fixed costs for the two standards. The lump sum investments are approximately $1.8 million in 1987 and $19.0 million in 1990 and reflect the aggregate costs for the standards. Expressed in other terms, the aggregate cost of compliance is equivalent to an investment of just under $2 per HDGE for the 1987 standard and just over $17 for the 1990 standard made in the years that each of the standards become effective. For ease of reference, the aggregate costs are shown in Table 3-17.

Table 3-17

Heavy-Duty Gasoline Engines, Aggregate Cost of Compliance for the 1987 and 1990 Standards (10 percent discount to January of year standard is introduced)

	1987	1990
Research, Development & Testing	$1,750K	$13,924K
Emission Control Hardware	--	5,027K
Total	$1,750K	$18,951K
Change in aggregate cost per 1 percent change in fuel economy of the fleet	$121M	$116M

C. Heavy-Duty Diesel Engines (HDDE) - NOx and Particulate Standards

In the case of HDDEs, four new standards are proposed: NOx and particulate standards for the 1987 model year and NOx and particulate standards for the 1990 model year. Manufacturer costs are developed for each standard by the format previously used for LDTs and HDGEs. The technologies which EPA expects that manufacturers will employ in meeting the standards were identified in Chapter 2 (Technological Feasibility). Application of these technologies forms the basis for the cost estimates developed below.

It should be noted that a relatively large number of technology combinations could be employed in meeting the proposed standards. For purposes of cost estimation, the approach used was to address the overall application picture rather than to attempt to identify specific combinations of technologies for each power rating within an engine family. Because the exact mix of technologies to be used is uncertain, there is also uncertainty in the cost estimates developed in this chapter. However, these estimates are believed to be representative of the actual costs manufacturers will incur.

1. Cost to HDDE Manufacturers of the 1987 Standards

a. Fixed Costs (research, development and testing (RD&T))

NOx Standard: HDDE manufacturers can be expected to meet the 1987 NOx standard by employing such techniques as injection timing retard and the addition of aftercooling* to some of the turbocharged engines which presently are not so equipped.

The work involved in implementing retarded injection timing can be viewed as being the equivalent of a calibration change. Because of the high priority which is placed on the fuel economy of HDDEs, it is reasonable to expect that manufacturers will evaluate several injection timing calibrations before selecting the calibration which results in minimum fuel economy penalty while complying with the emission standard. For purposes of developing this cost estimate it was assumed that three calibrations would be evaluated per engine family in the development of the final calibration. Assuming 160 hours of effort per calibration for the calibration changes, data collection and analysis plus a ten percent contingency factor, the development cost per engine family would be:

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* Aftercooling means cooling of the intake air after it is compressed by the turbocharger and prior to its entering the engine. Cooling of the pressurized intake air can be achieved by passing it through a heat exchanger which is cooled either by engine coolant or by ambient air or by a separate liquid coolant system. Aftercooling systems which use ambient air are referred to as air-to-air systems while the other systems are referred to as air-to-liquid systems.

3 calibrations x 160 hours/calibration x $50/hour x 1.1 contingency factor = $26,400.

The second design and development effort which was identified as being necessary for compliance with the 1987 model year NOx standard involves the application of aftercooling to some engines. The work required to accomplish this application would involve aftercooler sizing calculations, preparation of design and installation drawings, procurement of experimental parts, and some testing to confirm the performance of the aftercooler. Approximately six person-months of effort should suffice to accomplish this work. Using a cost of $50/hour to cover personnel, experimental parts and confirmatory testing plus a ten percent contingency factor, the cost per engine family would be:

6 person-months x 174 hours/person-month x $50/hour x 1.1 contingency factor = $57,400.

For the 1982 and 1983 model years, the sales mix between HDDEs which were turbocharged with aftercooling, turbocharged without aftercooling and non-turbocharged were approximately 41 percent, 21 percent and 38 percent respectively. As was stated previously, EPA expects that some, but not all, of the non-aftercooled engines will have aftercooling added. As a first estimate, it is assumed that approximately one-half of the non-aftercooled engines will have aftercooling added. This change would, therefore, impact approximately 10 percent of total engine sales.

Certification records show that 86 engine families were certified for the 1983 model year. While it is possible that some manufacturers may add engine families and that other manufacturers may enter the HDDE market, it is also possible that some engine families may be discontinued. Because it is not possible to quantify precisely what changes may occur, it was assumed that there will be no significant changes from 1983, in the number of engine families which will be certified in 1987 and 1990. Combining the cost estimates for each task which has just been developed, with the number of engine families involved, gives the development cost for the 1987 NOx standard as follows:

> $26,400/engine family for recalibration x 86 engine families + $57,400/engine family for aftercooling x 0.1 to account for the number of families which are involved x 86 engine families or approximately $2.8 million.

The third component of the fixed cost is the cost of certification. This cost will be estimated first in terms of the total cost of certification, followed by equal apportionment between the NOx and particulate standards. Continuing the conservative approach for estimating dynamometer-hour requirements addopted for HDGEs, but employing the relationship of 1,000 dynamometer hours as being equivalent to 100,000 miles of operation for HDDE (regulations applicable prior to 1984), the dynamometer-hour requirements are as follows. For HDDEs, the three lifetime mileages (110,000 miles for LHDDEs, 185,000 miles for MHDDEs and 290,000 miles for HHDDEs) are proportional to 1,100, 1,850, and 2,900 dynamometer hours. Applying the same contingency factor of ten percent as was used previously results in dynamometer requirements of 1,210 hours, 2,035 hours and 3,190 hours for the three groups. Combining these dynamometer-hour estimates with the appropriate distribution between engine families of the three groups permits development of an average dynamometer time requirement per engine family. Inspection of the engine descriptions for the 86 engine families certified for the 1983 model year shows: 1) that approximately 14 families represent 110,000-mile useful-life engines, 2) that approximately 16 families represent 185,000-mile useful-life engines, and 3) that approximately 56 families represent 290,000-mile useful life engines. Weighting the dynamometer hour requirements by these engine family values results in an average dynamometer hour requirement as follows:

> (14/86 x 1,210 hours) + (16/86 x 2,035 hours) + (56/86 x 3,190 hours) = 2,653 dynamometer hours per engine family.

Following the same methodology for HDDEs as was used for HDGEs in developing the certification cost estimate results in the following:

- One durability and three data engines per engine family, dynamometer operation time of 2,653 hours for the durability engine, and 130 hours per emission-data engine at a cost of $30 per hour results in a cost of $91,290.

- Emission tests at 150-hour intervals for the durability engines for a total of 17 tests and two tests per data engine at a cost of $2,000 per test results in a cost of $46,000.

Applying a 10 percent contingency factor to the sum of these costs and multiplying by the 86 engine families involved, results in a total cost for certification of approximately $13 million. Apportioning the certification costs equally between the NOx and the particulate standards, results in a per pollutant certification cost of $6.5 million.

The total fixed cost for the 1987 model year NOx standard would be the sum of the costs for injection timing calibrations, additional applications of aftercooling and certification and equals approximately $9.3 million. This value is shown in Table 3-18.

Particulate Standard: The technological changes which are expected to be employed by manufacturers in complying with the 1987 model year particulate standard were detailed in Chapter 2. In summary, the changes included: 1) modifications to the combustion chamber (probably through changes in the piston), 2) changes in injectors and increased injection pressure, 3) changes in the fuel delivery system so as to refine air/fuel ratio control during transient operation, and 4) changes to the turbocharger to improve air delivery characteristics during transients. A small (but not quantifiable) increase in the use of turbochargers which could benefit particulate control was also identified. Marketing forces will likely be, however, the primary reason for any increase in turbocharger use. Costs associated with this change are, therefore, not attributable to this regulation and are not included.

Changes in combustion chamber configuration through changes in the piston crown will involve some design effort, procurement of redesigned pistons and testing to establish the effects of the redesign. Changes in the injectors, injection pressure and the air/fuel controls would involve the same type of tasks as those required for the combustion chamber changes (i.e., some design effort, test part procurement and testing to establish the effects of the changes).

The costs associated with these four changes are derived on the basis of four person-months per design per component changed, assuming that one-half of the engines will require changes and allowing for two design changes per component to facilitate selection of the optimum design, as follows:

> 86 engine families x 1/2 (to account for half of the families being changed) x (4 + 4 + 4 + 4) person-months/change x 2 designs/change x 174 hours/month x $50/hour for personnel, parts and testing plus a ten percent contingency factor = $13,168,000 or approximately $13.2 million.

Table 3-18

Heavy-Duty Diesel Engines, Fixed
Costs of the 1987 NOx and Particulate Standards (1984 dollars)

Year	Non-Certification Costs		Certification Costs		Total Fixed Costs	
	NOx	Part.	NOx	Part.	NOx	Part.
1985	$2,000K	$12,000K	$1,000K	$1,000K	$3,000K	$13,000K
1986	800K	1,200K	5,500K	5,500K	6,300K	6,700K
Totals	$2,800K	$13,200K	$6,500K	$6,500K	$9,300K	$19,700K

Combining the estimated cost for development with the portion of the total certification cost previously developed for the 1987 model year particulate standard ($6.5 million) results in the total RD&T cost for the particulate standard of approximately $19.7 million. This cost is shown in Table 3-18.

Much, if not all, of the design and development work necessary for compliance with the 1987 model year NOx and particulate standards can reasonably be expected to be expended during 1985 with some of the longer leadtime certification testing also being performed in 1985. The apportionment of the design, development and certification costs between 1985 and 1986 together with the totals are shown in Table 3-18.

b. Emission Control System Hardware Costs for the 1987 Standards (Variable Cost)

NOx Standard: It is expected that changing fuel injection timing can be accomplished without any change in hardware. There are, therefore, no hardware costs associated with this change.

In developing the cost estimate for the aftercooler, it was assumed that these units would be air-to-liquid systems employing engine coolant as the medium for cooling the intake air and that the engine (truck) radiator does not have to be enlarged to accommodate the extra cooling load imposed. The components required for the aftercooler application would, therefore, be: 1) the heat exchanger and its housing which is introduced into the engine intake, modified engine intake system to provide plumbing for the intake air from the turbocharger to the aftercooler and from the aftercooler to the intake manifold, and 2) coolant hoses to and from the aftercooler. Using the cost estimate for an LDV radiator given in Reference 4 as the basis and assuming that the heat exchanger will be smaller than an LDV radiator, the estimated cost of the heat exchanger component of the aftercooler system is estimated to be approximately $41.* Reference 4 does not contain cost information which would allow direct development of an estimate for the costs of the aftercooler housing, intake air plumbing and coolant plumbing for the aftercooler. As a first estimate, a cost was assigned for these components which is approximately equivalent to one-half of the cost of the aftercooler heat exchanger, or $20. The total estimated cost for the aftercooler system is, therefore, $61 per engine. New engine list prices were checked as a method of evaluating this estimate. In all cases where aftercooled and non-aftercooled but otherwise similar engine pairs were compared, the aftercooled engine had a higher horsepower rating and a substantially higher price. Because marketing forces interrelate horsepower and price, the incremental price difference could not be attributed to the aftercooler. EPA believes that the cost estimate shown is a reasonable estimate of the aftercooler cost. With an aftercooler installation rate of 10 percent of sales, the total undiscounted costs are $2,141,000 in 1987, $2,233,000 in 1988, and $2,342,000 in 1989. These values are shown in Table 3-19.

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* $37.09 (1977 dollars) for the radiator assembly x 0.8 to account for reduced materials usage because of size reduction x (product of price inflation indices for 1978 through 1983 of 6.2, 7.4, 7.5, 6.8, 1.6, and 3.6 percent, respectively) = $40.90.

Particulate Standard: Little, if any, difference exists between the hardware costs of original design and redesigned components such as pistons, injectors, fuel metering and delivery systems and turbochargers. To be conservative, however, a per engine cost of $5 was assigned for each of the modified components (pistons, injectors, fuel metering and delivery and turbochargers) which are expected to be employed in meeting the 1987 model year particulate standard. This approach will also account for any additional hardware needed for improved air/fuel ratio control where none exists today. The total per engine cost for hardware would, therefore, be $20. Continuing the previously stated assumption that one-half of the engines produced could require these hardware modifications, results in hardware costs of $3,510,000 in 1987, $3,660,000 in 1988 and $3,840,000 in 1989. These costs are shown in Table 3-19.

c. Total Costs to Manufacturers for the 1987 HDDE Standards

The major undiscounted costs to manufacturers of RD&T and emission control hardware are $16.0 million for the NOx standard and $30.7 million for the particulate standard. The overall total is approximately $46.7 million as shown in Table 3-19. The discounted costs (1987) of $16.7 million, $33.1 million and $49.8 million for the NOx standard, the particulate standard, and the total respectively are shown in Table 3-20. The per engine discounted costs are also shown in Table 3-20 and are $15.14 for the NOx standard, $30.07 for the particulate standard and $45.21 for both standards.

Table 3-19

Heavy-Duty Diesel Engines; Manufacturers Undiscounted Costs of Compliance for the 1987 MY NOx and Particulate Standards

Year	RD & T		Emissions Hardware	
	NOx	Particulate	NOx	Particulate
1985	$3,000K	$13,000K	--	--
1986	6,300K	6,700K	--	--
1987	--	--	$2,141K	$3,510K
1988	--	--	2,233K	3,660K
1989	--	--	2,342K	3,840K
	$9,300K	$19,700K	$6,716K	$11,010K

Total Undiscounted Cost:

NOx:	$16,016K	(1984 dollars)
Particulate:	$30,710K	(1984 dollars)
Total:	$46,726K	

Table 3-20

Heavy-Duty Diesel Engines, Discounted Cost of Compliance for the 1987 Model Year NOx and Particulate Standards

Year	Cost			Present Value in 1987		
	NOx	Part.	Total	NOx	Part.	Total
1985	$3,000K	$13,000K	$16,000K	$3,630K	$15,730K	$19,360K
1986	6,300K	6,700K	13,000K	6,930K	7,370K	14,300K
1987	2,141K	3,510K	5,651K	2,141K	3,510K	5,651K
1988	2,233K	3,660K	5,893K	2,030K	3,327K	5,357K
1989	2,342K	3,840K	6,182K	1,936K	3,174K	5,110K
Total	$16,016K	$30,710K	$46,726K	$16,667K	$33,111K	$49,778K

Lump sum investment cost per engine made at the start of 1987

for the NOx standard:	$15.14
for the Particulate standard:	$30.07
for both standards:	$45.21

2. Cost to HDDE Manufacturers of the 1990 Standards

a. Fixed Costs (research development and testing (RD&T))

NOx Standard: In Chapter 2 (Technological Feasibility), technologies which may be employed in complying with the 1990 NOx standard were identified. As was pointed out in Chapter 2, some uncertainty exists with respect to these technologies. The estimate of cost developed below is, therefore, also subject to some uncertainty. These technologies were: 1) possibly some additional injection timing retard, 2) application of aftercooler systems which are designed to maximize the cooling of intake air through the use of either air or an auxiliary radiator for cooling, 3) application of EGR to prechamber engines, 4) modification of the compression ratio on some engines, and 5) the use of electronics for fuel injection and EGR control.

It is expected that manufacturers will employ essentially the same procedures in development of the optimum injection timing retard for the 1990 NOx standard as was employed for the 1987 NOx standard. The cost for this work was previously estimated as being $26,400 per engine family and will be used here.

Two methods of maximizing the cooling of the intake air charge have been identified. These methods are: 1) an air-to-air aftercooler system, or 2) an air-to-liquid aftercooler system similar to that which is presently used plus an auxiliary radiator for cooling of the aftercooler-system coolant. It appears reasonable to assume that manufacturers would avoid the use of fans whose sole function would be cooling of the aftercooler system because of their cost and parasitic losses. Expectations are, therefore, that manufacturers will design the aftercooler systems to employ either ram-air cooling or cooling by the existing radiator fan.

In the case of air-to-air aftercooler systems, HDDE manufacturer design and development costs would consist of development of the performance specification for the aftercooler system, design of the intake air plumbing from the turbocharger to the aftercooler heat exchanger and back to the engine, procurement of test parts, and testing to establish the performance of the system. Two factors can be expected to bear heavily on the level of effort which would be associated with this design approach. First, redesigns of the intake system can be expected. Second, this design approach has not been extensively used to date on HDDEs and manufacturers may tend to perform more development testing than they would otherwise. The level of effort associated with this task is estimated, therefore, to be 1.5 person-years per engine family at a cost of $50/hour to cover personnel, equipment and test cost. The cost per engine family is estimated, therefore, to be $172,200 including a 10 percent contingency factor.

For the air-to-liquid aftercooler system, it is expected that the design and development costs would be lower than those for the air-to-air system because the aftercooler heat exchanger and the engine intake system should not require modification. The new components will be the aftercooler radiator, coolant hoses and a pump for circulating the coolant. Testing requirements to establish the performance of the system could be less than with the air-to-air system because the lack of change in the intake system design would permit greater dependance on aftercooler radiator performance tests in place of total system tests. It is expected that the design and development costs for the air-to-liquid aftercooler system could be approximately one-third of that for the air-to-air system (i.e. $57,400 per engine family).

The third area where RD&T work can be expected is in the application of EGR to those LHDDEs which use prechamber design. One of these prechamber engines (GM product) is very similar to an EGR equipped LDT engine sold by that manufacturer. Direct technology transfer can be expected to occur which would preclude significant design and development costs for these engines. In the case of the other prechamber engine, design costs would be incurred for the application of EGR. The cost per engine family for this work can reasonably be expected to be similar to that which was previously estimated for LDDTs and is $86,000 including the cost of mechanical durability testing.

Changes in the compression ratio of some HDDEs constitutes the fourth area where RD&T costs may be incurred. This change could be accomplished through changes in the pistons and would incur costs similar to those previously estimated for combustion chamber changes; i.e., 2 designs/change x 4 person months/change x 174 hours/month x $50/hour plus 10 percent contingency = $76,600.

The application of electronic controls constitutes the final design and development task which was identified. The basic functions associated with the application of electronic controls to HDDEs can be identified as follows: the installation of sensors, the installation of actuators, installation of the control module, and the wiring necessary to interconnect the sensors, actuators and electronic module. Development of cost estimates for these functions pose significant problems as they relate to this regulation. Some manufacturers use vendor supplied fuel-injection systems and may, therefore, be able to purchase completely designed electronic control systems from vendors. Other manufacturers design their own fuel-injection systems and, as a result, may have to design much of the electronic-control system for their engines. In addition, manufacturers are known to be working on the development of electronic controls for HDDEs and may have complete systems, including the components necessary for NOx and particulate control, in production prior to the effective date of this regulation. The most probable reasons for the ongoing development work on electronic controls for HDDEs are improvements in fuel economy which may be realized and manufacturers' desires to increase their capabilities for compliance with stringent emission standards. Only a part of the cost of developing electronic controls for HDDEs should reasonably be allocated, therefore, to the control of emissions. Based upon this analysis, a design, development and test cost of $208,800 (two person-years at $50/hour) per engine family was assigned for the work of developing electronic controls for both the fuel injection and the EGR systems. An equal division of the costs between the NOx and particulate standards was also chosen.

The cost of certification testing was previously estimated as being $6.5 million per emission standard for the 1987 standards. This cost will also be used for the 1990 standards.

The overall fixed cost for the 1990 NOx standard is developed by weighting the individual cost estimates by the number of engine families which are expected to require each of the technologies as follows:

- 86 engine families x $26,400/engine family for injection timing modifications = $2,270,000.
- Application of aftercooling to all families except the 14 LHDDE families: (86-14) x [($177,200 + $57,400)/2], assuming equal distribution between the two aftercooler design approaches = $8,266,000.
- Application of EGR to one engine family = $86,000.
- Changes in piston design on 25 percent of the engine families: (86/4) x $76,600 = $1,685,000.
- 86 engine families employing electronic controls x ($208,800)/2 per engine family x 1.1 (10 percent contingency factor) = $9,876,000.

- 86 engine families being certified at a cost of $6,500,000.

The total fixed cost estimate is the sum of the individual components and is $28,683,000, or approximately $28.7 million.

RD&T work directed to meeting the 1990 NOx standard can reasonably be expected to begin in 1987 and to continue into 1989. The projected distribution of these costs is shown in Table 3-21.

Particulate Standard: Particulate trap technology is presently in the transition stage from research to relatively low volume production for some 1985 model year LDDVs. It is reasonable to expect, therefore, that a relatively high level of effort would be expended by each of the larger manufacturers of HDDEs, with appropriate interfacing with trap manufacturers, in the design and development of particulate trap systems for HDDEs. These efforts are expected to focus first on the development by each of the larger manufacturers of a general system design which possesses the desired durability and trap efficiency and then on the design and development of engine family specific systems. In the case of HDDE manufacturers which are either relatively small or which have low sales volumes in the United States, it is reasonable to expect that there would be a dependence upon the trap manufacturers for the general system design, followed by the engine manufacturer's development of engine family specific designs.

With the exception of Ford, all larger manufacturers of heavy-duty trucks which also produce cars and/or lighter duty trucks are manufacturers of HDDEs. To be conservative, it was assumed that Ford could enter the HDDE market by 1990 with the result that there would be seven HDDE manufacturers which would develop their own general system designs. The other manufacturers would be expected to rely on particulate trap suppliers for the general system designs. As a first estimate, it is expected that each of the larger manufacturers could expend 20 person-years of effort in the 1986-87 timeframe in the initial development of a general system design. This work would entail higher expenditures for experimental parts, test engines and fuel than would be expended in the development of engine family specific designs. The cost of $50 per hour which has been used previously in developing cost estimates for design and development will be increased to $60/hour for this effort. On a per manufacturer basis, the cost of developing the general design is estimated to be 20 person-years x 2088 hours per year x $60 per hour or $2,506,000.

Table 3-21

Heavy-Duty Diesel Engines, Fixed Costs for the 1990 NOx and Particulate Standards

Year	Non-Certification Costs		Certification Costs		Total Fixed Costs	
	NOx	Part.	NOx	Part.	NOx	Part.
1986	--	$8,000K	--	--	--	$ 8,000K
1987	$7,000K	20,000K	--	--	$7,000K	20,000K
1988	14,000K	13,000K	1,000K	1,000K	15,000K	14,000K
1989	1,200K	2,000K	5,500K	5,500K	6,700K	7,500K
Total	22,200K	43,000K	6,500K	6,500K	28,700K	$49,500K

Design, development and system performance testing for the engine family specific designs is estimated to require two person-years of effort per design. The cost of this effort is estimated to be 2 person-years x 2088 hours per year x $50 per hour or $208,800 per engine family.

It is anticipated that 30 percent of the HDDE families may not require the use of particulate trap systems as a result of averaging in determinations of compliance with the particulate standard. The total, industry wide, fixed cost for the design of the particulate trap system is, therefore, estimated to be $30,112,000 (($2,506,000 x 7 manufacturers) + ($208,800 x 86 x 0.7 engine families)) exclusive of any contingency factor. With a 10 percent contingency factor, the total cost becomes $33,123,000.

The first cost for applying electronic controls to HDDE attributable to these regulations has previously been estimated at $19,752,000, equally divided between the NOx and particulate standards, (i.e. $9,876,000 for the particulate standard).

The final component of the first cost of the particulate standard is the cost of certification which was previously estimated at $6.5 million per emission standard.

Summing the component parts of the first cost results in a total first cost estimate of $49,499,000 or approximately $49.5 million. These RD&T costs can reasonably be expected to be expended between 1986 and 1989 as shown in Table 3-21.

b. Emission Control System Hardware Costs (Variable Cost) for the 1990 Standards

NOx Standard: Hardware costs attributable to the 1990 NOx standard for HDDEs would accrue from the use of such technologies as aftercooling systems, electronic engine controls, modified pistons and the application of EGR. The estimates for the cost of each of these hardware changes will be developed separately followed by appropriate sales weightings to develop the total hardware cost estimate.

As was discussed previously, two aftercooler design approaches can be employed, (i.e. air-to-air systems or air-to-liquid systems). It was also indicated previously that aftercooler designs are expected to avoid the use of an additional cooling fan. This approach would result in the placement of either the air-to-air aftercooler or the radiator section of the air-to-liquid system in front of the engine radiator. While some small increase in the temperature of the cooling air will occur as the air passes over the aftercooler, it is expected that the increase will not be great enough to necessitate an increase in the size of the engine radiator.

For the case of the air-to-air aftercooler system, the aftercooler would be very similar in appearance and construction to an engine radiator but would have the pressurized engine intake air passing through it rather than engine coolant as in the case of a radiator. The cost of this component can, therefore, be derived from the cost estimate for a LDV radiator as given in Reference 4. The size of the aftercooler and, therefore, the amount of materials used in its construction are expected to be larger, however, than that of a radiator on a LDV. A sizing factor of 30 percent was assigned to account for the size differential. The resulting cost of the air-to-air aftercooler is approximately $67. As was pointed out previously, Reference 4 does not contain data upon which the cost estimate of the intake air plumbing can be based. In this case, the extent of the plumbing change will be greater than that required in the aftercooler design for the 1987 standard. In addition, the plumbing will have to include flexible components to allow for motion of the engine relative to the aftercooler. As a first estimate, the cost chosen for the plumbing equals that of the aftercooler, (i.e., $67). The total estimated cost for the air-to-air aftercooler system is the sum of these two costs (i.e. $134 per engine).

In those cases where a manufacturer chooses to replace an existing air-to-liquid system which is cooled by engine coolant with an air-to-air system, the hardware cost would be the value just calculated less the cost of components removed. For the 1987 standard, the cost of adding an air-to-liquid system which used engine coolant was estimated to be $61. The differential hardware cost for the system replacement design approach would, therefore, be $73 ($134 - $61).

In the case of air-to-liquid systems which change from the use of engine coolant as the cooling medium to a separate aftercooler radiator, the anticipated new components are: 1) the aftercooler radiator, 2) hoses to connect the two heat exchangers, 3) a coolant circulation pump, 4) belt drive from the engine to the pump, and 5) support bracketry for the pump. The aftercooler radiator would be very similar to the engine radiator of a LDV and its cost can be derived directly from Reference 4, (i.e. $51). The cost estimates for the other components are assigned values because applicable data is not contained in Reference 4. The estimated costs are: $25 for the pump and support bracketry, $10 for the hoses, and $5 for the belt drive. The total for the components is $40, which when combined with the cost of the aftercooler radiator, gives a system cost of $91.

The cost of applying an air-to-liquid system to an engine which was not previously intercooled would consist of the cost just developed ($91) plus the cost of the aftercooler at the engine which was previously estimated as being $61. The total cost would, therefore, be $152. Because this cost is higher than the cost of using an air-to-air system ($134) it was assumed that this approach would not be extensively employed on engines which were not intercooled.

As was previously shown (Fixed Costs for the 1987 HDDE NOx standard) the sales split between engines which are turbocharged with aftercooling, turbochared without aftercooling and non-turbocharged was 41 percent, 21 percent and 38 percent respectively. As was also shown previously, approximately one half of the non-intercooled turbocharged engines can be expected to receive aftercooling as a result of the 1987 NOx standard (i.e., 10 percent of sales will be intercooled for the first time). As a result of the 1990 NOx standard, it is expected that aftercooling may be applied to all turbochared engines and that a 50/50 split could occur between the use of air-to-air systems and air-to-liquid systems. The 11 percent of sales which receive aftercooling for the first time (21 percent - 10 percent) as a result of the 1990 standard are assumed to use air-to-air systems and represent 18 percent (11/62) of turbocharged engine sales. With a 50/50 split between the two aftercooler systems, 32 percent of the existing aftercooler systems would be modified to air-to-air systems. The remaining 50 percent of the existing systems would be converted from an air-to-liquid system using engine coolant to an air-to-liquid system using a separate radiator. The average hardware cost per turbocharged engine for improved aftercooling is calculated as follows:

- 18 percent of all turbocharged engines receive aftercooling for the first time and use air-to-air systems which cost $134 for a per turbocharged engine cost contribution of $24.12.

- 32 percent of all turbocharged engines are converted from air-to-liquid systems to air-to-air systems at a cost differential of $73. The per turbocharged engine cost contribution is $23.36.

- 50 percent of all turbocharged engines are converted from air-to-liquid systems using engine coolant to air-to-liquid systems using separate aftercooler radiators. The system hardware cost for this design approach is $91 for a per engine cost contribution of $45.50.

The average cost per turbocharged engine is the sum of the three components, or approximately $93. It was assumed that the sales split between turbocharged and non-turbochared HDDE remains relatively stable at the 1982 level (i.e., 62 percent turborcharged). With 62 percent of HDDEs being turbocharged, the per engine cost expressed in terms of all HDDEs is approximately $58.

The cost of adding EGR to a LDDT was previously estimated as being $20. This cost will be used for the engines of the LHDDE family which are expected to have EGR applied for the first time. This cost is considered to be reasonable because of the general similarity which exists between the engine of a LDDT and a LHDDE. Between five and ten percent of the production engines are expected to have EGR fitted for the first time. Using the larger percentage value, the per engine cost for all engines is $2.

For those engines which employ redesigned pistons, the previously adopted conservative approach will be continued and a hardware cost increase of $5 per engine is assigned. Assuming that 25 percent of all engines are equipped with redesigned pistons, the per engine cost for all engines is $1.25.

In Reference 1, the cost of an electronic control module was estimated as being $75 with equal prorating of the cost between NOx and particulate control. The cost of a sensor for determining trap temperature was estimated as being $12. This cost will be used as the basis for developing the estimates of costs of sensors for NOx control systems. Sensors which will be employed as part of the electronic control system for NOx control will monitor engine speed, load, rate of change of load, coolant temperature, intake air temperature and pressure. The temperature sensors, while being essentially on/off units similar to those used on the particulate trap, will operate in a less thermally demanding environment than that of the particulate trap. Their cost will, therefore, be lower and is estimated to be $6 each. The other sensors will be required to deliver proportional signals rather than on/off signals and will, therefore, be more costly. Their cost is estimated to be 50 percent higher than that of the trap temperature sensor or $18 each. The cost of the wiring harness connecting the sensors, electronic control module and the actuator is estimated to be $15[4]. The final components of the electronic control system are the actuators which will modulate fuel delivery and EGR as directed by the control module. While Reference 4 does not contain any data on the cost of an actuator, it is reasonable to expect that the actuator will be an electrical stepper motor which very precisely and rapidly translates the control module signal into either linear or circular motion. As a first estimate, a cost of $40 has been assigned to the actuator for the fuel delivery system and $25 to the actuator for the EGR system. Summing the costs of the component parts of the electronic control system gives the estimate of the cost of the system for NOx control as follows:

> $37.50 for the control module + 2 sensors at $6 each + 4 sensors at $18 each + $15 for the wiring harness + $40 for the fuel actuator + $25 for the EGR actuator for a total of $201.50 or approximately $202.

The total hardware cost per engine for the NOx standard is the sum of the components, (i.e. $58 for aftercooling, $2 for the application of EGR, $1.25 for redesigned pistons and $202 for electronic controls). The total hardware cost per HDDE for the NOx standard is therefore, approximately $263. Because of uncertainties with respect to the exact mix of technologies which will be used by manufacturers, the cost which actually occurs could be either lower or higher than this estimated value.

Particulate Standard: In the Diesel Particulate Study,[1] estimates were developed for the hardware costs of particulate trap systems for both catalyzed and non-catalyzed traps. The system hardware costs developed in Reference 1 are reproduced and summarized in Table 3-22.

Assuming equal performance for the two system types (catalyzed and non-catalyzed) with respect to durability and trap efficiency, differences in first price and fuel economy will dominate manufacturers decisions on system selection. To overcome the first cost differential, catalyzed systems would have to exhibit lifetime fuel economy benefits relative to non-catalyzed systems on the order of 1 percent, 1.5 percent and 4.5 percent for HHDDE, MHDDE, and LHDDEs, respectively.* EPA expects that there will be little, if any, difference in fuel economy between the two system types and has concluded that manufacturers will probably select the non-catalyzed system. Combining the costs for the non-catalyzed systems with the expected sales distributions between LHDDEs (33 percent) MHDDEs (25 percent) and HHDDEs (42 percent)[1] gives the average hardware cost per engine of $533 for engines equipped

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* System cost differential divided by the undiscounted, lifetime fuel economy cost differentials of $900, $390, and $86 per one percent change in fuel economy for HHDDEs, MHDDEs, and LHDDEs, respectively.

Table 3-22

Heavy-Duty Diesel Engines, Particulate Trap System Hardware Costs per Engine[3]

HDDE Group	Non-Catalyzed Trap			Catalyzed Trap		
	Trap	Regeneration System	Total System	Trap	Regeneration System	Total System
LHDDE	$207	$156	$363	$636	$118	$754
MHDDE	343	213	556	1,051	156	1,207
HHDDE	403	249	652	1,252	192	1,444

with particulate-trap systems. Allowing for the reduced installation rate of particulate-trap systems which results from averaging (30 percent are not expected to use trap systems), the per engine cost for all HDDEs is $373.

c. Total Cost to Manufacturers of the 1990 Standards

The total RD&T and emission hardware costs (undiscounted) are shown in Table 3-23 for the years in which they are expected to occur. The undiscounted costs to manufacturers of RD&T and emission control hardware are estimated to be $354.3 million for the NOx standard and $511.3 million for the particulate standard. The projected overall total for the 1990 NOx and particulate standards is $865.6 million as shown in Table 3-23. The discounted costs are shown in Table 3-24 and are $330.7 million for the NOx standard, $483.2 million for the particulate standard for a total of $813.9 million.

3. Costs to Users (HDDE - NOx and particulate)

a. Increases In First Cost

The amount that a manufacturer must increase the price of its HDDEs to recover its expenses depends on the timing of the costs and on the cost of capital to the manufacturer. In the case of HDDEs, new NOx and particulate standards will become effective in the 1987 and again in the 1990 model years. It is expected that manufacturers of HDDEs face a 10 percent cost of capital and that they will increase the engine prices to recover their pre-production costs in the three model years following introduction of each of these new standards. The increase in first cost is determined below on the basis of each model year in which new standards become effective and for the contribution by each of the standards as well as for the total increase.

1987 Model Year Standards: The average increase in first cost of HDDEs would consist of the sum of the hardware cost as shown in Table 3-25 plus the discounted fixed cost as shown in Table 3-26. For the NOx standard, these costs are $6.10 for hardware and $9.59 for the fixed costs for a total of $15.69 or approximately $16. In the case of the particulate standard, the contributions to the total first cost increase of $30.98 or approximately $31 are $20.98 from fixed costs and $10.00 from hardware costs. The total increase in first cost is the sum of the costs from the two standards and is $46.67 or approximately $47.

Table 3-23

Heavy-Duty Diesel Engines, Manufacturers Undiscounted Compliance Costs for the 1990 MY NOx and Particulate Standards

	RD & T		Emissions Hardware	
Year	NOx	Particulate	NOx	Particulate
1986	--	$ 8,000K	--	--
1987	7,000K	20,000K	--	--
1988	$15,000K	$14,000K	--	--
1989	$6,700K	$7,500K	--	--
1990	--	--	$103,096K	$146,216K
1991	--	--	$108,093K	$153,303K
1992	--	--	$114,405K	$162,255K
	$28,700K	$49,500K	$325,594K	$461,774K

Total Undiscounted Cost:
NOx: $354,294K (1984 dollars)
Particulate: $511,274K (1984 dollars)

Total: $865,568K

Table 3-24

Heavy-Duty Diesel Engines,
Discounted Cost of Compliance for
the 1990 Model Year NOx and Particulate Standards

Year	Cost			Present Value in 1990		
	NOx	Part.	Total	NOx	Part.	Total
1986	--	$8,000K	$8,000K	--	$11,713K	$11,713K
1987	7,000K	20,000K	27,000K	9,317K	26,620K	35,937K
1988	15,000K	14,000K	29,000K	18,150K	16,940K	35,090K
1989	6,700K	7,500K	14,200K	7,370K	8,250K	15,620K
1990	103,096K	146,216K	249,312K	103,096K	146,216K	249,312K
1991	108,093K	153,303K	261,396K	98,266K	139,366K	237,632K
1992	114,405K	162,255K	276,660K	94,550K	134,095K	228,645K
Total	354,294K	511,274K	865,568K	330,749K	483,200K	813,949K

Lump sum investment cost per engine made at the start of 1990:

for the NOx standard:	$267.16
for the particulate standard:	$390.31
for both standards:	$657.47

Table 3-25

Heavy-Duty Diesel Engines, Undiscounted
Costs of Compliance with the Standards per
Engine for Engines Produced During 1987-89 and 1990-92

	1987-89			1990-92		
Manufacturer Cost	NOx	Part.	Total	NOx	Part.	Total
Research, Development & Testing	$8.45	$17.89	$26.34	$23.18	$39.98	$63.16
Emission Control Hardware	6.10	10.00	16.10	263.00	373.00	636.00
Total	$14.55	$27.89	$42.44	$286.18	$412.98	$699.16

Operating Cost

Change in Fuel Cost per one
Percent Change in Fuel Economy for LHDDE: $ 86.02
for MHDDE: $389.61
for HHDDE: $900.43
for all HDDE: $503.97

Table 3-26

Heavy-Duty Diesel Engines, Discounted Costs of Compliance per Engine for Engines Produced During 1987-89 and 1990-92[1]

	1987-89			1990-92		
Manufacturer Cost	NOx	Part.	Total	NOx	Part.	Total
Research, Development & Testing	$9.59	$20.98	$30.57	$28.14	$51.32	$79.45
Emission Control Hardware	5.55	9.09	14.64	239.02	339.00	578.02
Total	$15.14	$30.07	$45.21	$267.16	$390.31	$657.47

Operating Cost

Change in Fuel Cost per one Percent Change in Fuel Economy		
	for LHDDE:	$ 58.13
	for MHDDE:	$274.18
	for HHDDE:	$660.55
	for all HDDE:	$365.16

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[1] 10 percent discount rate to year standard is introduced.

1990 Model Year Standards: The components of the first cost increase for the 1990 standards are shown in Tables 3-25 and 3-26. The first cost components of the NOx standard per engine for all engines built are estimated to be $28.14 for fixed costs and $263 for hardware for a total first cost increase attributed to the NOx standard of $291.14 or approximately $291. On the basis of all engines built, the first cost increase resulting from the particulate standard is $424.31 or approximately $424 consisting of $51.31 fixed cost and $373.00 hardware cost. The overall first cost increases for the NOx and particulate standards is estimated to be $715.45 or approximately $715. For the three HDDE classes, the first price increases are $597 for LHDDEs, $732 for MHDDEs and $799 for HHDDEs on the basis of all engines. The first cost increases for engines using particulate trap systems are; $705 for LHDDEs, $898 for MHDDEs, $994 for HHDDEs, and $875 for the sales weighted average.

b. Fuel Economy

In Chapter 2, Technological Feasibility, it was estimated that fuel economy penalties associated with the 1987 and 1990 model year NOx standards would be in the range of 0 percent to 2 percent for each of the standards in the short term. These penalties should both tend to disappear with time as further engine and vehicle improvements are made. In the case of the particulate standards, a long term fuel economy penalty of between 1 and 2 percent may be associated with the 1990 standard. A fuel economy penalty associated with the 1987 particulate standard is not expected.

In Reference 1, fuel economy estimates for LHDDEs, MHDDEs, and HHDDEs of 15.5 mpg, 8.4 mpg, and 7.0 mpg, respectively were developed. Combining these fuel economy values with a fuel cost of $1.20 per gallon and with annual mileages and lifetimes of 11,000 miles per year for 10 years, 30,000 miles per year for 9 years, and 65,000 miles per year for 8 years for LHDDEs, MHDDEs, and HHDDEs, respectively, allows development of fuel economy cost estimates. A 10 percent discount rate is employed and the fuel economy cost estimates for each engine class were sales weighted in arriving at the average cost per engine and total average lifetime cost. The sales fractions used are 33 percent LHDDE, 25 percent MHDDE, and 42 percent HHDDE.

Based on the above figures, each one percent reduction in fuel economy corresponds to an annual increase in fuel usage of 7.17 gallons for LHDDEs, 36.07 gallons for MHDDEs, and 93.80 gallons for HHDDEs. These increases in fuel usage correspond to lifetime costs of $58.13 for LHDDEs, $274.18 for MHDDEs, and $660.55 for HHDDEs. Sales weighting of these costs gives the average lifetime cost for a 1 percent change in fuel economy of $365.16.

Applying these average costs, the range in the fuel economy cost, per engine, which corresponds to the 0 to 2 percent change in fuel economy expected to be associated with the 1987 NOx standard is $0 to $730.32. It is expected that no fuel economy costs will be associated with the particulate standard for 1987. In terms of the overall fuel economy costs for the 1987 standards the range is, therefore, between $0 and $730.32 per engine. For the engines produced in 1987 through 1989, the total cost for the fuel economy penalty could be up to $804 million.

In the case of the 1990 model year standards, fuel economy costs are expected to result from both the NOx and the particulate standards. For the NOx standard, the range for the fuel economy penalty is between $0 and $730.32 while the range for the particulate standard is between $365.16 and $730.32. The range, per engine, for the overall fuel economy effect for the two standards is, therefore, between $365.16 and $1,460.64. Because of the previously stated expected removal of any fuel economy penalty due to the NOx standard through engine and vehicle improvements, the upper bound of this range can be expected to decrease to $730. Expressed in terms of the total number of engines which are expected to be produced in 1990 through 1992, the total cost is projected to be between $452 million and $1.81 billion initially, decreasing to an upper limit of $905 million.

c. Maintenance

Maintenance costs are not expected to be affected by either the 1987 NOx or particulate standards for HDDEs.

In the case of the 1990 standards some increase in maintenance costs, for some of the engines, can reasonably be expected for both the NOx and the particulate standards. For those engines which add a separate air-to-liquid aftercooling system (50 percent of turbochared engines or 31 percent of all engines), maintenance to drain, flush and refill the system can be expected to occur twice during the lifetime of the engine. It is also reasonable to expect that the circulation pump drive belt will be replaced when the other maintenance is performed. The cost at each of these maintenance points is estimated to be $15 for labor and materials for a total lifetime cost of $30. When expressed in terms of all HDDEs, this maintenance cost represents a per engine cost of $9.30. Application of air-to-liquid aftercoolers can reasonably be expected to occur on MHDDE and HHDDEs exclusively. With lifetimes of nine years and eight years for MHDDE and HHDDE respectively, maintenance of the aftercooler system can be expected to occur at three years and six years into the lives of the engines. Discounting the maintenance costs at 10 percent per year gives a total discounted cost of approximately $20 per engine requiring the maintenance and just over $6 per engine when expressed in terms of all HDDEs.

In Reference 1, estimates were developed for the effects on maintenance costs of particulate-trap systems. It is expected that the trap-regeneration system will require maintenance once during the engine lifetime. The cost for this maintenance was projeted to be $35 per engine for LHDDEs and $70 per engine for both MHDDEs and HHDDEs occuring approximately fives years after the engine was purchased. It is also expected that there will be a maintenance saving attributable to the particulate standard. This saving would come from the use of stainless steel exhaust pipe which would last the life of the engine in place of the presently used mild steel which could be replaced once during the engine's lifetime. The savings in maintenance which were estimated in Reference 1 for the three HDDE classes were $63, $98, and $156 for LHDDE, MHDDE and HHDDEs respectively. The net effects on maintenance costs for the particulate standards are, therefore, savings of $28 for LHDDE and MHDDE and $86 for HHDDE. When discounted to the year of purchase, the savings in maintenance are $17 for LHDDE and MHDDE and $53 HHDDE. The average sales-weighted saving per engine is approximately $32. The overall effect on maintenance costs for the 1990 NOx and particulate standards is a saving of approximately $26 per HDDE ($32-$6).

d. Total Costs to Users

In summary, owners of vehicles which are equipped with HDDEs can be expected to pay an average of approximately $47 more in 1987 and $715 more in 1990 for these vehicles than they would have paid without the introduction of the NOx and particulate standards.

In terms of fuel costs, the increased average lifetime cost per vehicle is expected to be between $0 and $730 as a result of the 1987 standards and to be between $365 and $1,461 for the 1990 standards.

Maintenance costs are not expected to be affected by the 1987 standards. Savings of approximately $26 per engine are expected to occur as a result of the 1990 standards. The total costs of the 1987 and 1990 standards to users of HDDEs are shown in Table 3-27.

Table 3-27

Heavy-Duty Diesel Engines; User Cost per Engine for the 1987 and 1990 Standards (discounted* to year that standard becomes effective)

	1987 Standards	1990 Standards
First Price	$47	$715
Maintenance	0	($26)
Fuel	$0 to $730	$365 to $1,461

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* 10 percent per year.

4. Aggregate Costs

The aggregate costs are shown in Table 3-28. For the 1987 HDDE standards the fixed and hardware costs are $49.8 million and between $0 and $804 million for fuel. The aggregate cost for the 1987 standards is, therefore, between approximately $50 million and $854 million. In the case of the 1990 model year standards the fixed and hardware costs are $814 million, between $452 million and $1.81 billion for fuel and maintenance savings of $32 million for an aggregate cost range of between $1.23 billion and $2.59 billion.

The aggregate costs for the 1990 standards (HDGEs and HDDEs) were previously presented as representing the equivalent of a one time expenditure made at the time that the standards become effective, i.e., 1990. The aggregate costs of the 1990 standards can also be treated as a one time expenditure made in 1987. This approach would result in all aggregate costs of the component parts of this action being expressed as lump sum expenditures in a common year. On this basis, the aggregate costs in 1987 are $1.08 billion for LDTs, $16.0 million for HDGEs, $661.4 million for HDDEs, and between $316 million and $2.14 billion in fuel attributable to HDDEs.

II. Socioeconomic Impact

The costs of the standards which were developed in the first section of this chapter are used here to analyze the effects of the standards on manufacturers, regional employment, and the nation as a whole. The effects on manufacturers will be analyzed with respect to sales, capital investment, and cash flow. Nationally, the effects of the standards will be analyzed with respect to vehicle purchasers and users, energy usage, balance of trade, and inflation.

A. Effects on Manufacturers

1. Sales

Estimates of the effects of an increase in price on vehicle sales can be developed from the price elasticity of demand for the vehicle type under analysis, the price increase, and the price of the vehicle type prior to the increase.

Jack Faucett Associates (JFA) estimates that the price elasticity of demand for all LDTs is approximately -1.0.[6] This value is considered by JFA to be equally applicable to diesel and gasoline-powered LDTs. In the 1983 model year, prices of LDTs ranged from a low of approximately $6,000 for a small LDT with the base gasoline engine and no optional

Table 3-28

Heavy-Duty Diesel Engines,
Aggregate Cost of Compliance for
the 1987 and 1990 Standards (10 percent
discount to January of year standard is introduced)

	1987 Standard	1990 Standards
Research, Development & Testing	$33,660K	$98,360K
Emission Control Hardware	$16,118K	$715,589K
Fuel Economy	$0 to $804,082K	$452,068K to $1,808,272K
Maintenance	0	($32,188K)
Total	$49,778K to $853,860K	$1,233,829K to $2,590,033K

equipment to a high of about $15,000 for a large LDT fully equipped with optional accessories and powered by a diesel engine. Prices for an average gasoline LDT and an average diesel LDT would be within these limits and can be considered to be approximately $9,000 and $10,000, respectively. The average price increases for gasoline LDTs and diesel LDTs attributed to the NOx standard are $87 and $35, respectively. These numerical price increases represent a 0.97 percent increase in the price of a gasoline LDT and a 0.35 percent increase in the price of a diesel LDT. With a price elasticity of demand of -1.0, the price increases are projected to result in a 0.97 percent reduction in the sales of gasoline LDTs and a 0.35 percent reduction in the sales of diesel LDTs.

The historical trend in LDT sales has been that of a growth market; i.e., yearly sales increases, with the exception of the recent past where sales of all consumer goods have declined. During 1983, sales of LDTs have increased with the general strengthening of the national economy. It is expected that the return to the historical pattern will continue and that the projected sales decrease will be reflected as a smaller rate of growth in sales rather than an actual decrease in sales. Values for cross-price elasticity of demand were not available and it was not possible, therefore, to develop an estimates of the shift in demand between engine types (either from gasoline to diesel or from diesel to gasoline). It appears reasonable, however, that some very small shift toward diesels may occur because of the greater price increase of gasoline LDTs. It is expected that there will be no significant effect on either fuel economy or maintenance as a result of the NOx standard. Neither of these factors are expected, therefore, to have any effect on LDT sales.

Development of estimates for the effects of the new standards on sales of HDTs will follow the same procedure as were used for LDTs. The price range for HDTs starts at approximately the upper level for LDTs ($15,000), and continues through approximately $100,000. Representative first prices for the groups of vehicles included in the HDT class are: $18,000 for a LHDGT, $20,000 for a LHDDT, $25,000 for a MHDGT, $28,000 for a MHDDT, and $55,000 for a HHDDT. In Reference 7, Jack Faucett Associates gave price elasticity of demand values for four of these HDT classes as follows: -1.0 for LHDGTs, -1.0 to -1.2 for MHDGTs, -1.0 to -1.5 for MHDDTs, and -0.35 to -0.8 for HHDDTs. A value was not given for LHDDTs. For this analysis, a value of -1.0 is assumed for LHDDTs which is the same value as is used for LDDTs and LHDGTs.

In the cost section of this chapter, the price increase for HDGEs was estimated as being $2 in 1987 and $18 in 1990. Expressing these price increases as percentage changes of first price and incorporating the price elasticity of demand values, give projected percentile reductions in HDGT sales of between 0.01 and 0.02 in 1987 and between 0.06 and 0.09 in 1990.

For the 1987 standards, the average price increase for HDDEs was estimated to be $47. This price increase, coupled with the highest price elasticity values for each class, results in projected sales reductions of 0.17 percent for LHDDTs, 0.18 percent for MHDDTs, and 0.05 percent for HHDDTs.

For the 1990 model year standards, the average price increase for HDDEs was estimated to be $715. Because of the variation by class in the first prices and the projected price increases of HDDTs, the average price increase will not be used in the development of estimates of the effects on sales. For LHDDTs, the estimated price increase of $597 ($291 from the NOx standard and $306 from the particulate standard) represents a 2.99 percent increase in first price. For MHDDTs and HHDDTs, the estimated price increases of $732 ($291 for NOx and $441 for particulate) and $799 ($291 for NOx and $508 for particulate) represent 2.61 and 1.45 percent increases in first price, respectively. Combining these values with the price elasticity values from Reference 7 results in projected decreases in sales of 2.99 percent for LHDDTs, between 2.61 and 3.92 percent for MHDDTs, and between 0.51 and 1.16 percent for HHDDTs. The fractions of the projected sales decreases attributable to the NOx and particulate standards are proportional to the fractions of the cost increase contributed by each standard. For LHDDTs, the NOx standard contributes a projected sales decrease of 1.46 percent and the particulate standard contributes 1.53 percent of the total 2.99 percent. For MHDDTs, the percentile sales reduction range for the NOx standard is between 1.04 and 1.56 percent while the range for the particulate standard is 1.57 to 2.36 percent. Corresponding values for HHDDTs are between 0.19 and 0.42 percent for the NOx standard and betwen 0.32 and 0.74 percent for the particulate standard.

For the 1987 standards, the effects of first price increases on sales for both gasoline and diesel-powered HDTs are projected to be so small as to be reasonably considered to be negligible. For the 1990 standards, it is also reasonable to conclude that the sales of gasoline-powered HDTs will not be significantly impacted by the increase in first price. For diesel-powered HDTs, the first price increases could result in a reduction in sales on the order of 2-1/2 to 4 percent in the light-heavy and medium-heavy duty classes. The projected reduction in sales for the heavy-heavy duty class is on the order of 1/2 to 1 percent which is significantly less than in the other two classes.

For HDGEs, it is not expected that the new emission standards will have any effects on either fuel economy or maintenance and consequently it is not expected that these factors will have an impact on sales.

For HDDEs taken as a group, it is expected that the 1987 standards will result in a sales-weighted average cost increases for fuel of between $0 and $730 attributable totally to the NOx standard. For the three HDDE classes, the cost increases for increased fuel usage are between $0 and $116 for LHDDEs, between $0 and $548 for MHDDEs, and between $0 and $1,321 for HHDDEs. It is expected that there will be no effect on maintenance costs associated with the 1987 standards for HDDEs. Combining the fuel and maintenance costs (zero) with the operating cost elasticity of demand (-0.3 to -0.9) given in Reference 6 results in projected percentile sales decreases for the three classes of HDDEs as follows: 1) for LHDDEs a sales decrease of between 0 and 0.52 percent, 2) for MHDDEs a sales decrease of between 0 and 1.76 percent, and 3) for HHDDEs a sales decrease of between 0 and 2.16 percent.

For the 1990 standards, the increases in fuel cost are contributed approximately equally by the NOx and particulate standards. The ranges for the three HDDE classes are: 1) between $58 and $232 for LHDDEs, 2) between $274 and $1,096 for MHDDEs, and 3) between $661 and $2,644 for HHDDEs. For the 1990 standards, it is expected that there will be reductions in maintenance costs for LHDDEs and MHDDEs of $11 and of $47 for HHDDEs. The net increases in operating costs (fuel costs - savings in maintenance) are projected to result in reduced sales of the three HDDE classes as follows: 1) between 0.07 and 0.99 percent for LHDDEs, 2) between 0.28 and 3.49 percent for MHDDEs, and 3) between 0.33 and 4.25 percent for HHDDEs. The NOx and particulate standards make approximately equal contributions to the projected reductions in sales.

The projected effects on sales of LDTs, HDGEs, and HDDEs resulting from first price increases and changes in operating costs are summarized in Table 3-29. For the 1987 standards, the projected effects on sales are as follows: essentially no effect in the case of HDGEs, under 1 percent reduction in sales of LDGTs and LDDTs stemming from first price increase and up to approximately a 2-1/3 percent decrease in the sales of HDDE caused mainly by increased fuel usage. Sales of HDGEs are not expected to be significantly affected by the 1990 standards. Sales of LHDDEs could be reduced between 3 and 4 percent as a

Table 3-29

Projected Effects Of the 1987 and 1990 Standards On Sales Of LDTs, HDGEs, and HDDEs (percentile reductions)

	1987 Standards				1990 Standards			
	LDGT	LDDT	HDGE	HDDE	HDGE	LHDDE	MHDDE	HHDDE
First Price Increase	0.97	0.35	0.01 to 0.02	0.05 to 0.18	0.06 to 0.09	2.99	2.61 to 3.92	0.51 to 1.16
Operating Costs	0	0	0	0 to 2.16	0	0.07 to 0.99	0.28 to 3.49	0.33 to 4.25
Total	0.97	0.35	0.01 to 0.02	0.05 to 2.34	0.06 to 0.09	3.06 to 3.98	2.89 to 7.41	0.84 to 5.41

result of the 1990 standards, with first price increase playing the major roll in the decrease. For MHDDEs, first price increase and increased fuel usage contribute about equally to the projected sales decrease of between 3 and 7-1/2 percent. For HHDDEs, the projected sales decrease is from just under 1 to 5-1/2 percent caused mainly by increased fuel usage.

Because the costs of purchasing and operating diesels are expected to be increased by the 1990 standards with little corresponding change for gasoline engines, it is reasonable to expect that some small shift to gasoline engines could occur. Any shift which may occur is not expected to be significant, however, because the inherent fuel economy advantage and consequently operating cost advantage of diesel engines will not be compromised.

Like the LDT industry, the HDE industry has historically exhibited a growth trend. This trend is expected to continue. The projected reductions in sales of HDEs are expected, therefore, to be translated into a reduction in the rate of growth of sales rather than an actual reduction in sales.

2. Development Costs and Cash Flow

Manufacturers of LDTs and HDEs will not have to make any substantial investments as a result of either the 1987 standards or the 1990 standards. Preproduction costs are not very large and will be recovered within 3 to 5 years of the effective dates of the standards.

The bulk of the development costs associated with the required use of trap-oxidizers is expected to be borne by the manufacturers of emission control equipment, such as Corning, NGK, and Johnson-Matthey. The manufacturers of reducing catalysts which will be employed on LDTs have already developed the necessary technology. Even though the manufacturers of emission control equipment will have to finance the necessary investments, they all have indicated their willingness and ability to supply this market. Thus, pre-production investment costs should not be a problem for any affected entities.

The impact on cash flow will result from the inventory of reducing catalysts and particulate traps which a manufacturer has on-hand at any given time. In Reference 1, 90 days were identified as the average period of time that an LDT is normally held by a manufacturer, with a corresponding figure for HDDVs of under four months. These turnover periods should be short enough not to significantly affect a manufacturers cash flow.

B. Regional Effects

Manufacturers operate about 22 plants in assembling LDTs in the U.S. The locations for each manufacturer are shown in Table 3-30. A total of 12 states are included. General Motors operates nine assembly plants to produce LDTs and vans. Some of these plants are also used to assemble passenger cars. GM has plants located in seven states with three in Michigan. Ford Motor Company (Ford) operates seven assembly plants spread over seven states. Chrysler and American Motors Corporation (AMC) currently operate two each and IHC and Nissan operate one each. Domestic manufacturers of HDEs and HDVs currently operate assembly plants in 17 different states, as shown in Table 3-31.

As can be seen in Tables 3-30 and 3-31, there is a broad dispersion across the country of manufacturing facilities which could be impacted by the standards. Because of this dispersion of facilities, any negative effect of the standards with respect to employment will not be concentrated in one or more areas of the country. As was stated previously, it is expected that the cost increases associated with the standards will translate into a decrease in the rate of growth of the affected industries rather than an actual reduction in sales. The impact on employment can reasonably be expected, therefore, to be either a slowing in the rate at which new employees are hired or a reduction in overtime rather than a reduction in jobs.

C. National Effects

1. Vehicle Purchasers and Users

Purchasers of LDTs and vehicles equipped with HDEs could be affected to some degree by the higher vehicle first costs. It is not expected, however, that the effects will be significant because the price increases are small when expressed as a percentage increase in first price (i.e., from a low of essentially zero to a high of approximately three in the case of LHDDEs). The expected average sales-weighted first cost increase in 1987 of $74 for LDTs and of $715 in 1990 for HDDE should not substantially impact the purchaser's ability to pay for either a new LDT or a new HDV.

Users of HDVs powered by diesel engines can be expected to be affected to some degree by the higher first cost and operating cost of vehicles employed to transport goods. These increased costs can reasonably be expected to be passed on as higher freight costs which in turn will affect the prices consumers pay for the products transported by diesel trucks.

Table 3-30

Light Truck Assembly Plants in the United States

General Motors:

- Fremont, California
- Lakewood, Georgia
- Baltimore, Maryland
- Detroit, Michigan
- Flint, Michigan
- Pontiac, Michigan
- St. Louis, Missouri
- Lordstown, Ohio
- Janesville, Wisconsin

Ford:

- San Jose, California
- Louisville, Kentucky
- Wayne, Michigan
- Twin Cities, Minnesota
- Kansas City, Missouri
- Lorain, Ohio
- Norfolk, Virginia

Chrysler:

- Warren, Michigan
- St. Louis, Missouri

American Motors:

- Toledo, Ohio
- South Bend, Indiana

International Harvester:

- Fort Wayne, Indiana

Nissan:

- Smyrna, Tennessee

Table 3-31

States with HDE and HDV Manufacturing Plants

HDE Plants	HDV Plants
California	California
Illinois	Indiana
Indiana	Missouri
Kentucky	New York
Michigan	Ohio
Ohio	Oregon
Oklahoma	Pennsylvania
Pennsylvania	Tennessee
	Texas
	Utah
	Virginia
	Washington
	Wisconsin

Freight costs are, however, only a relatively small fraction of the cost of a product and any small increase in freight cost will be reflected as a proportionally smaller increase in product cost.

2. Energy Usage

The effects on energy usage of these standards are expected to be limited to HDDEs. As stated previously, each 1 percent decrease in the fuel economy of a HDDE means a lifetime operating cost increase of approximately $365. In terms of the increased volume of fuel used, each 1 percent reduction in fuel economy represents an increase in lifetime fuel usage of 420 gallons for an average HDDE. On an annual basis, the average HDDE is expected to use an additional 50.8 gallons of fuel for each 1 percent reduction in fuel economy. With an average annual sales volume of 413,000 HDDEs (mean of 1990-92 sales estimates) and fleet replacement every 9 years, each 1 percent reduction in fuel economy results in increased fuel usage of 21 million gallons in the first year of the standards increasing to 189 million gallons in the tenth year of the standards. Combining these values with the projected fuel economy effects of the 1987 NOx standard (i.e., between zero and two percent reduction) gives projected increases in fuel usage of between 0 and 42 million gallons in the first year of the standard increasing to between 0 and 378 million gallons in the tenth year of the standard. For the 1990 NOx and particuate standards, increased fuel usage is expected to be between 21 million and 84 million gallons in the first year of the standard, increasing to between 189 million and 756 million gallons in the tenth year of the standard. The yearly effects of the HDDE standards on fuel usage are shown in Table 3-32.

3. Balance of Trade Effects

The implementation of three-way catalyst technology over oxidation catalyst technology on LDTs will cause an increase in the imports of noble metals, primarily rhodium and platinum. Imports of palladium are expected to decrease.

The incremental changes in noble metal imports discussed below are the changes which are expected to occur as a result of the implementation of the revised NOx standard for LDTs and incorporate the 4-, 6-, and 8-cylinder engine sales split expected in the late 1980's. The change in these imports is shown below:

Table 3-32

Yearly Increases in Fuel Usage by HDDEs
Resulting From the 1987 and 1990 Standards

Year	Increased Annual Fuel Usage (millions of gallons)
1988	0 to 42
1989	0 to 84
1990	0 to 126
1991	21 to 210
1992	42 to 294
1993	63 to 378
1994	84 to 462
1995	105 to 546
1996	126 to 630
1997	147 to 672
1998	168 to 714
1999	189 to 756

Annual Noble Metal Imports Due to LDTs (Troy oz)

	1987 No Revised NOx Std	1987 Revised NOx Std
Platinum	158,386	389,829
Palladium	87,227	47,329
Rhodium	0	32,811

At prevailing market prices, these figures translate into increases of approximately $74.8 million for platinum, $20.2 million for rhodium, and a decrease of $6.9 million due to palladium. The sum of these three figures yields an increase in imports of about $88.1 million per year. These figures depend on the composition and loading of catalytic materials used on each vehicle and will vary as a function of the differences between the systems used by manufacturers and those assumed in this analysis.

Another effect on the balance of trade of the standards comes from the first price increase of imported LDTs, most of which use 4-cylinder gasoline engines. Based on the first price increases in Table 3-13, this comes to about $120 per 4-cylinder LDT ((($108 + $131)/2). If it is assumed that 40 percent of the 4-cylinder market is imported, this average price increase yields a loss in the balance of trade about $50.1 million per year based on the average of the yearly sales shown in Table 3-1.

The third effect on the balance of trade of the new standards comes from increased fuel usage by HDDEs. As was previously estimated, increases in fuel usage are expected to be between 0 and 42 million gallons in 1988 rising to between 189 million and 756 million gallons in 1999. Assuming that each additional gallon of fuel used represents an increase in oil imports of 1 gallon*, and using a cost of $30 per barrel (1 barrel = 42 gallons), increased fuel usage by HDDEs translates into increased oil importation costs of up to $30 million in 1988 and between $135 million and $540 million in 1999.

4. Inflationary Effects - Consumer Price Index

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* While one gallon of imported crude oil does not produce one gallon of diesel fuel, the other products produced from the crude oil would tend toward a national over supply of these products which could then be exported. The national balance of trade would, therefore, be approximately as assumed.

The consumer price index (CPI) is one of the primary indications for changes in the general price level. It has been estimated that LDTs contribute about 0.5 percent to the CPI determination and that HDEs contribute a similar percentage.[8] Combining these percent contributions with the average estimated price increase of about 2 percent for both LDTs and vehicles using HDEs, will give only a .01 percent increase in the CPI for each of the regulated classes of vehicles. Needless to say this increase is negligible compared to other elements of the CPI. Therefore, it is concluded that these emission regulations will have no significant price level impact as measured by the CPI. Further, since the public will receive air quality and related health improvements in exchange for the higher prices, the rise in the CPI that will occur cannot properly be termed inflationary.

References

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3. "The Impact of Light-Duty Diesel Particulate Standards on the Level of Diesel Penetration in the Light-Duty Vehicle and Light-Duty Truck Markets," Jack Faucett Associates, EPA Contract No. 68-01-6375, January 17, 1983.

4. "Cost Estimations for Emission Control Related Components/Systems and Cost Methodology Description," Rath & Strong Inc., EPA-460/3-78-002, March 1978.

5. Oral Communication with the Bureau of Labor Statistics.

6. Oral communication with Jack Faucett Associates.

7. "Estimation of Economic Elasticities In the Heavy-Duty Vehicle Market," Jack Faucett Associates, EPA Contract No. 68-01-6375, February 23, 1983.

8. "Preliminary Impact Assessment of the Non-Passenger Automobile Fuel Economy Standards for Model Years 1980 and 1981," Planning and Evaluation Office of Program Analysis, DOT, NHTSA, November 29, 1977.

Chapter 4

NOx ENVIRONMENTAL IMPACT

I. Introduction

This chapter examines the environmental effects which can be expected from implementing the proposed NOx standards for light-duty trucks (LDTs) and heavy-duty engines (HDEs) in non-California locations of the United States. The emission inventory and air quality analyses presented in this chapter are based on the implementation of split-class NOx standards for LDTs and two-stage standards for HDEs, beginning in the 1987 model year. Class I LDTs, i.e., those up to 6,000 lbs gross vehicle weight (GVW) or 3,999 lbs equivalent test weight, would meet a standard of 1.2 g/mi, while LDTs from 6,001 to 8,500 lbs GVW (Class IIa) would conform to a standard of 1.7 g/mi. Beginning in the 1987 model year, HDEs would meet a 6.0 g/BHP-hr NOx standard. For 1990 and later model year engines this standard would be reduced to 4.0 g/BHP-hr.

The impact assessment begins with a brief review of the most recent and significant health and welfare effects associated with NOx emissions and provides references to more comprehensive studies. Following this, LDT and HDE emission rates are presented for both base-case (current levels of NOx control) and controlled-case (new standards) scenarios. A statutory-standard case is also included for comparison purposes to show the reductions that would be possible if the statutory standards were technologically practicable for all HDEs. The effects of implementation of the above-mentioned standards are then quantified in terms of the lifetime per-vehicle NOx emission reductions and total area-wide NO_2 inventory reductions from an analysis of Standard Metropolitan Statistical Areas (SMSAs) which have high concentrations of nitrogen dioxide (NO_2). The net effects of reductions in total NOx tonnage for these designated SMSAs is then described in terms of projected improvements in NO_2 ambient air quality.

II. Health Effects

A concise analysis of NO_2 health effects is difficult to present due to the abundance of NO_2 health effects research data and the scientific debate which results when interpreting these studies. Two comprehensive sources of NO_2 health effects information are currently available and the concerned reader is referred to these reports. They are the EPA publications: "Air Quality Criteria for Oxides of Nitrogen"[1] (the Criteria Document), and the "Review of the National Ambient Air Quality Standards for Nitrogen Oxides: Assessment of Scientific and Technical Information - OAQPS Staff Paper"[2] (the OAQPS Staff Paper).

An overview of the NO_2 health effects may be provided as follows. Mild symptomatic effects at NO_2 concentrations approaching short-term peak ambient exposures (0.5 ppm NO_2 for two hours) have been observed in asthmatics. In general, adverse health effects, such as pulmonary function impairment, are only observed at NO_2 concentrations in excess of 1.0 ppm, while adverse health effects are inconclusive at exposure levels below 0.5 ppm. However, the NO_2 health effects research contains convincing evidence from animal studies which shows serious biological effects from long-term exposure to slightly elevated ambient concentrations of NO_2. These findings suggest a definite risk to human health from chronic exposure to NO_2, but such risks have not been quantified at current ambient NO_2 levels.[2] More recently, epidemiology studies have suggested concern over the health impacts of repeated short-term exposure. These results report increased rates of acute respiratory illness and impaired pulmonary function, particularly among sensitive population groups, such as children.[2]

The Criteria Document presents complete and detailed information from animal toxicology, controlled human exposure, and epidemiology studies. A summary and analysis of selected studies are presented in the OAQPS Staff Report, with additional comments by the Clean Air Science Advisory Committee, an independent oversight committee composed of members from academia and industry which reviewed the OAQPS Staff Report.[3]

III. Air Quality Analysis

The previous sections briefly summarized the health and welfare effects of NOx in the environment and referenced more definitive studies. This section will quantify the contributions of LDTs and HDEs to local NOx inventories and predict the resulting changes in ambient NO_2 concentrations if the NOx emission standards are changed. Specifically, this part of the analysis will present: 1) a discussion of EPA mobile source emission factors, 2) an estimate of the per vehicle reduction in NOx emissions, 3) base-case, controlled-case, and statutory-case NO_2 inventories for standard metropolitan statistical areas (SMSAs) with relatively high ambient NO_2 concentrations, and 4) projections of the net effects on local ambient air quality that will result from enacting new NOx standards for LDTs and HDEs.

The three scenarios used in this analysis are based on the following NOx emission standards:

Effective Year	LDTs (g/mi)	HDEs (g/BHP-hr)
Base Case	2.3	10.7
Controlled Case:		
1987	1.2 (Class I) 1.7 (Class IIa)	6.0
1990	1.2 (Class I) 1.7 (Class IIa)	4.0
Statutory Case:		
1987	0.9	1.7

Base-case standards represent the current NOx emission standards. The 1.2/1.7 and 6.0 NOx standards are proposed to be effective for 1987 model year LDTs and HDEs, respectively, and the 4.0 standard for HDEs would be effective with the 1990 model year. A third scenario is included representing the statutory standards of 0.9 g/mi* for LDTs and 1.7 g/BHP-hr for HDEs, effective with the 1987 model year.

A. Emission Factors

Emission factors are emission rates, expressed in grams per mile, used to calculate mass quantities of pollutants emitted. Mobile source emission factors are based on an analysis of emission test results from in-service LDVs and LDTs from the ongoing EPA Emission Factors Program, and from baseline studies of heavy-duty engines. Emission factors equations take the form:

$$ER = ZM + DR(m)$$

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* 0.9 g/mi represents a 75 percent reduction from baseline levels. This standard is not being proposed because it represents a stringency greater than that of the light-duty vehicle standards. The 1.2 g/mi and 1.7 g/mi standards have been selected as equivalent in stringency to light-duty vehicle standards of 1.0 g/mi and 1.5 g/mi

Where ER is the emission rate, ZM represents zero mile emissions and DR(m) is the deterioration rate per 10,000 mile increment multiplied by the mileage (in tens of thousands). Once emission factor equations for each model year's vehicles are established, composite emission factors for a particular vehicle class and a specific calendar year are determined using registration and mileage weighted emission factors.

Tables 4-1 and 4-2 summarize emission rate information for four mobile source emission classes: 1) LDGTs, 2) LDDTs, 3) HDGVs, and 4) HDDVs. The meaning of the "ZM" and "DR" columns is described above. The "SEA" column refers to Selective Enforcement Audit, which is EPA's assembly line testing program performed at a manufacturer's assembly plant. The 40 percent criterion represents the Acceptable Quality Level (AOL), or maximum failure rate, included in SEA testing. The AQL affects the emission factor calculation, and the results in Tables 4-1 and 4-2 reflect this adjustment. The "Useful-Life" column designates the period for which the manufacturers must certify the emissions compliance of their vehicles/engines. These periods are generally referred to as the half or full "useful life" of the vehicle or engine. Terms of the emission factor equations for full-life periods are generally lower than for half-life periods, since emission levels are required to be below the standard for the full life of the vehicle or engine, rather than for only half the lifetime.

As was discussed above, the mobile source emission factors for particular vehicle/engine types in given model years are weighted according to number of registrations and mileage to yield composite average emission rates for an emission class in a specific calendar year. Because of this aggregation, mobile source emission factors represent a matrix of emission results based on time (model year) and mileage (deterioration rate). The composite emission factors are calculated using a modified version of the MOBILE2 program, an EPA computer model which calculates composite NO_2 emission factors for the following vehicle types: 1) LDGVs, 2) 0-6,000 lb LDGTs (LDGT Is), 3) 6,001-8,500 lb LDGTs (LDGT IIs), 4) HDGVs, 5) LDDVs, 6) LDDTs, and 7) HDDVs. The MOBILE2 program is described in detail in references [15] and [16].

B. Per-Vehicle NOx Reductions

A common method of quantifying the anticipated emission reduction benefits of new emission standards is to determine the difference in average per-vehicle lifetime emissions for vehicles assumed to operate under the base- and controlled-case emission standards. Lifetime emissions are straightforward calculations requiring only the emission rate data of Tables 4-1 and 4-2, and estimates of the lifetime mileages for the appropriate vehicle classes. The results summarized in Tables 4-3 and 4-4 are based on the following lifetime mileages:

Table 4-1

NOx Emission Rates and Assumptions Different Than MOBILE2 Values for Emission Inventory and Air Quality Analysis

Low Altitude

	Vehicle Type	Model Year	Emission Rate			Useful Life[4]
			ZM[1]	DR[2]	SEA[3]	
Base Case:	LDGT	1984	1.89	0.10	40%	Half
		1985+	1.85	0.08	40%	Full
	LDDT	1984	1.89	0.07	40%	Half
		1985+	1.84	0.07	40%	Full
	HDGV	1984	9.45	0.09	--	Half
		1985	9.45	0.07	--	Full
		1986+	9.45	0.07	40%	Full
	HDDV	1984	26.72	0.20	--	Half
		1985	26.04	0.07	--	Full
		1986-95	24.80	0.06	40%	Full
Controlled Case:	LDGT	1984-86		Same as Base Case		
	Cl. I[5]	1987+	1.00	0.06	40%	Full
	Cl. IIa[6]	1987+	1.38	0.04	40%	Full
	LDDT	1984-86		Same as Base Case		
	Cl. I[5]	1987+	0.93	0.06	40%	Full
	Cl. IIa[6]	1987+	1.31	0.06	40%	Full
	HDGV	1984-86		Same as Base Case		
		1987-89	8.23	0.06	40%	Full
		1990+	5.44	0.05	40%	Full
	HDDV	1984-86		Same as Base Case		
		1987-89	20.94	0.06	40%	Full
		1990-95	13.70	0.06	40%	Full

Table 4-1 (cont'd)

NOx Emission Rates and Assumptions Different Than MOBILE2 Values for Emission Inventory and Air Quality Analysis

Low Altitude

	Vehicle Type	Model Year	Emission Rate ZM[1]	Emission Rate DR[2]	Emission Rate SEA[3]	Useful Life[4]
Statutory Case:	LDGT	1984-86	Same As Base Case			
		1987+	0.76	0.07	40%	
	LDDT	1984-86	Same As Base Case			
		1987+	0.71	0.05	40%	Full
	HDGV	1984-86	Same as Base Case			
		1987+	2.45	0.08	40%	Full
	HDDV	1984-86	Same As Base Case			
		1987-95	6.15	0.05	40%	Full

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[1] Zero-mile emissions (g/mi).
[2] Deterioration rate (g/mi-10K mi).
[3] Selective Enforcement Audit.
[4] Certification to half or full useful life.
[5] Less than 6,000 lbs GVW.
[6] 6,001 - 8,500 lbs GVW.

Table 4-2

NOx Emission Rates and Assumptions Different than MOBILE2 Values for Emission Inventory and Air Quality Analysis

High Altitude

	Vehicle Type	Model Year	Emission Rate		SEA	Life
			ZM	DR		
Base Case:	LDGT	1984	1.55	0.09	40%	Half
		1985+	1.51	0.07	40%	Full
	LDDT	1984	1.89	0.07	40%	Half
		1985+	1.84	0.06	40%	Full
	HDGV	1984	6.29	0.09	40%	Half
		1985	6.29	0.07	--	Full
		1986+	6.29	0.07	40%	Full
	HDDV	1984	26.72	0.20	--	--
		1985	26.04	0.07	--	Full
		1986-95	24.80	0.06	40%	Full
Controlled Case:	LDGT	1984-86	Same as Base Case			
	Cl. I	1987+	0.90	0.05	40%	Full
	Cl. IIa	1987+	1.13	0.03	40%	Full
	LDDT	1984-86	Same as Base Case			
	Cl. I	1987+	0.93	0.06	40%	Full
	Cl. IIa	1987+	1.31	0.06	40%	Full
	HDGV	1984-86	Same as Base Case			
		1987-89	5.48	0.06	40%	Full
		1990+	3.62	0.05	40%	Full
	HDDV	1984-86	Same as Base Case			
		1987-89	20.94	0.06	40%	Full
		1990-95	13.70	0.06	40%	Full
Statutory Case:	LDGT	1984-86	Same As Base Case			
		1987+	0.74	0.07	40%	Full
	LDDT	1984-86	Same As Base Case			
		1987+	0.71	0.05	40%	Full
	HDGV	1984-86	Same As Base Case			
		1987+	2.32	0.08	40%	Full
	HDDV	1984-86	Same As Base Case			
		1987-95	6.15	0.05	40%	Full

Table 4-3

Average Per-Vehicle Total Lifetime NOx Emissions and Percent Reductions

Low Altitude

Vehicle Class	Base Case[1] (tons)	Controlled Case[2] (tons)	Percent Reduction	Statutory Case[3] (tons)	Percent Reduction
Light-Duty Gasoline Trucks - Class I[4]	0.31	0.18	41.6	0.16	49.4
- Class IIa[5]	0.31	0.21	30.5	0.16	49.4
Light-Duty Diesel Trucks - Class I[4]	0.30	0.17	42.9	0.13	55.3
- Class IIa[5]	0.30	0.22	26.1	0.13	55.3
Heavy-Duty Gasoline (1987)	1.19	1.04	13.0	0.35	70.6
Heavy-Duty Gasoline (1990)		0.69	41.9		
Heavy-Duty Diesel (1987)	9.82	8.33	15.2	2.58	73.7
Heavy-Duty Diesel (1990)		5.54	43.6		

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[1] Base-case emissions are calculated using 1985 model year emission rates for LDTs and 1986 emission rates for HDVs.

[2] Controlled-case emissions are calculated using 1987 model year emission rates for LDTs and 1987 and 1990 model year emission rates for HDVs.

[3] Statutory case emissions are calculated using 1987 model year emission rates for LDTs and HDVs.

[4] 0-6,000 lbs GVW

[5] 6,001-8,500 lbs GVW

Table 4-4

Average Per-Vehicle Total Lifetime NOx Emissions and Percent Reductions

High Altitude

Vehicle Class	Base Case[1] (tons)	Controlled Case[2] (tons)	Percent Reduction	Statutory Case[3] (tons)	Percent Reduction
Light-Duty Gasoline Trucks-Class I[4]	0.26	0.16	37.8	0.15	39.9
- Class IIa[5]	0.26	0.17	32.1	0.15	39.9
Light-Duty Diesel Trucks- All	0.29	0.17	41.4	0.13	54.1
Heavy-Duty Gasoline (1987)	0.81	0.71	13.0	0.34	58.7
Heavy-Duty Gasoline (1990)		0.47	41.6		
Heavy-Duty Diesel (1987)	9.82	8.33	15.2	2.58	73.7
Heavy-Duty Diesel (1990)		5.54	43.6		

---

[1] Base-case emissions are calculated using 1985 model year emission rates for LDTs and 1986 emission rates for HDEs.

[2] Controlled-case emissions are calculated using 1987 model year emission rates for LDTs and 1987 and 1990 model year emission rates for HDVs.

[3] Statutory-case emissions are calculated using 1987 model year emission rates for LDTs and HDVs.

[4] 0-6,000 lbs GVW

[5] 6,001-8,500 lbs GVW

LDTs	120,000 mi
HDGVs	110,000 mi
HDDVs	350,000 mi

The lifetime periods are based on analyses conducted as part of the recently promulgated full-life useful-life regulations for LDTs and HDVs. The LDT and HDGV lifetime mileages are the typical usage periods for most vehicles in the respective classes, while the HDDV lifetime mileage represents a weighted composite for all HDDVs based on usage and rebuild characteristics of a wide variety of vehicles and engines.[17]

Tables 4-3 and 4-4 show significant NOx reductions from all truck classes as a result of implementation of the proposed standards. HDVs show the greatest reductions in terms of absolute tons of pollutant per vehicle, however, it is important to remember that many more LDTs than HDVs are sold each year, so LDTs do indeed contribute a substantial portion of the total NOx inventory. Per-vehicle lifetime emissions would be reduced by 26-43 percent for LDTs, while HDV emissions would be reduced by 13-15 percent under the 1987 standards. The NOx reduction for HDVs increases to 42-44 percent over current levels with the implementation of the second stage of the HDE standards in 1990.

C. NOx Emission Inventories

1. NOx Problem Areas

NOx emission inventory projections and the resulting air quality impacts estimates were performed for designated high NO_2 SMSAs, where high NO_2 areas are defined as non-California SMSAs which exceeded NO_2 concentrations of 0.04 ppm (annual arithmetic mean) in the base year in question. This value ensures the inclusion of areas at or near (within 25 percent) of the NAAQS of 0.053 ppm. The annual average ambient NO_2 concentrations are termed "design values," and are used to specify the base year condition for calculating NOx emissions inventories and ambient air quality projections. Values for 1980 and 1981 (the two latest available) were used for purposes of this analysis. Use of a range in design values provides a range of emission inventory and air quality projections. This, in turn, removes the sensitivity of the results to short-term changes in ambient NO_2 concentration. For example, some recent reductions in ambient NO_2 concentrations for the 1981 calendar year may reflect a reduction in industrial activity rather than a true and stable improvement in air quality. The high NO_2 areas, which include six low-altitude and two high-altitude areas, and their 1980 and 1981 design values, are presented in Table 4-5.

2. The EPA Rollback Model

Tables 4-1, 4-2, and 4-6 display the input data to the modified MOBILE2 model, the results of which are then used in the EPA Rollback Model to calculate the NOx emission inventory and air quality projections for future years.[18] The Rollback Model is used to model the relationship between changes in source emissions and changes in air quality concentrations. The model is linear, so changes in source emissions rates result in proportional changes in emission inventories and air quality concentrations. The information presented in Tables 4-1 and 4-2 has previously been described in the Emission Factors discussion. The information presented in Table 4-6 requires some interpretation, however. The first column, labeled "Designation," refers to the particular emission source class. The LDT class includes information pertinent to both LDGTs and LDDTs. The "Off-Highway" class includes mobile sources such as aircraft, railroad, marine, construction, and agricultural equipment. The "Combustion" source designation is typically associated with NOx produced by furnaces and boilers for commerical and residential heating. "Stationary Area" sources include all other combustion sources and otherwise unaccounted NOx sources in a particular area.

The mobile source growth rate information presented in the second column represents the estimated percent change, relative to a base condition, of the numbers of vehicle miles travelled which are expected for EPA's best estimate of a "medium" level growth rate. The area stationary source growth rate information for other sources is based on changes in the number of sources.

The third column represents the replacement of existing NOx sources with new ones. Because mobile source replacement rates are a function of the source type and model year, they are numerous, and therefore they are presented in the MOBILE2 documentation.[15,16]

The discount factors shown in Column 4 are used to adjust emission sources for varying air quality impacts by inserting a multiplicative factor in the MOBILE2 program. This factor may vary from 0 to 1 and is used to adjust the emission inventory values to more accurately model the given source category. Discount factors other than 1.0 are often used to account for the fact that stationary point sources with high effective

Table 4-5

Standard Metropolitan Statistical Areas with High Ambient NO_2

SMSAs	NO_2 Annual Average Concentration (ppm) 1980 Design Values	NO_2 Annual Average Concentration (ppm) 1981 Design Values
Boston, MA	0.050	0.038
Chicago, IL	0.060	0.050
Cleveland, OH	0.048	0.039
Nashville, TN	0.047	0.049
Philadelphia, PA	0.046	0.046
Steubenville, OH	0.040	0.039
Denver-Boulder, CO[1]	0.046	0.044
Reno, NV[1]	0.048	0.043

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[1] High-altitude areas.

Table 4-6

Annual Growth and Replacement Rates, and Discount Factors

Designation	Growth Rate 1977-95 Medium (percent)	Replacement Rates (percent)	Discount Factor
LDGV	+1.7	As In MOBILE2	1.0
LDT	+4.7	As In MOBILE2	1.0
HDGV	-0.3	As In MOBILE2	1.0
LDDV	+1.7	As In MOBILE2	1.0
HDDV	+6.4	As In MOBILE2	1.0
Stationary Point	+3.5	+4.3	0.0
Off-Highway	+2.5	0.0	1.0
Combustion	+0.8	0.0	1.0
Stationary Area	0.0	0.0	1.0

stack heights do not significantly affect the pollutant concentration in the immediate local area. In this analysis, stationary point source contributions are deducted from the emission inventory and air quality calculations by using a value of zero for the discount factor. This is because mobile and area sources, rather than point sources, are likely to be the principal cause of high annual average NO_2 concentrations at urban monitoring sites.

Figures 4-1, 4-2, and 4-3 summarize the discounted NOx emission inventory results using the base-case scenario (no new NOx standards), the controlled-case scenario (the proposed standards), and the statutory-standard scenario, respectively, for low-altitude areas. Each set of emission projections includes total NOx emissions from six source types for each of the calendar years 1980, 1983, 1987, 1988, 1990, and 1995, along with the percentages of total emissions represented by each class. Figures 4-4, 4-5, and 4-6 provide the same information for high-altitude areas. Figures 4-7 and 4-8 show the low- and high-altitude trends for emissions from individual vehicle classes. The following sections discuss the results for each of the three control scenarios separately.

3. Low-Altitude Emission Inventories

a. Base Case

The discounted results for the base case (i.e., no new standards) presented in Figure 4-1 can most easily be interpreted by examining the data trends for a particular emission source as a function of time. For example, the stationary area source contribution in Figure 4-1 is projected to remain nearly constant through 1995, while the contributions from off-highway sources is shown to increase in both total number of tons and the percent of total NOx emissions. The total increase for these two sources is 50,200 tons which represents a 23 percent increase. The mobile source total increases by some 71,600 tons, or an increase of 17 percent, despite decreases in both the LDV and HDGV portions of the inventory. The contributions from LDVs indicate a steady decline in the mass quantities of NOx as vehicles designed to meet a lower NOx standard replace older, higher emitting vehicles. Between 1983 and 1995 the LDT NOx contribution is projected to increase by some 13,900 tons (an increase of 42 percent), despite the replacement of trucks designed to meet 3.1 g/mi NOx standards before 1979 by trucks certified to meet the 2.3 g/mi standard starting with the 1979 model year. This increase is due to the projected increase in LDT usage in future years. HDGVs on the other hand show a slight decrease, on the order of 1,500 tons or 5 percent, in total NOx emissions, even without imposition of new NOx standards. This decline is due to the decrease in the projected numbers of

Figure 4-1
NOX EMISSIONS INVENTORY
HIGH NO2 URBAN AREAS
Base Case Projections
Low Altitude

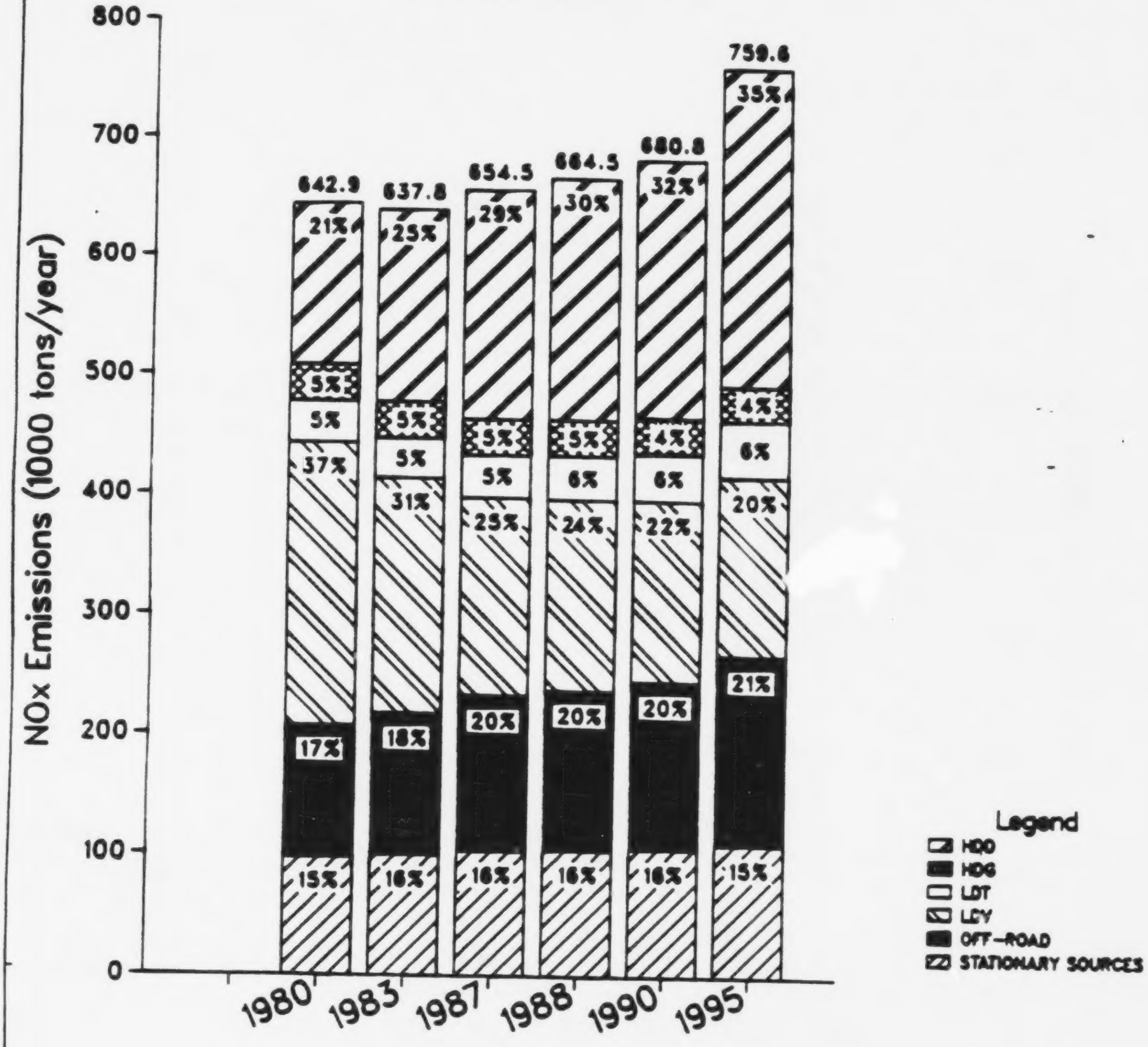


Figure 4-2
NOX EMISSIONS INVENTORY
HIGH NO2 URBAN AREAS
Controlled Case Projections
Low Altitude

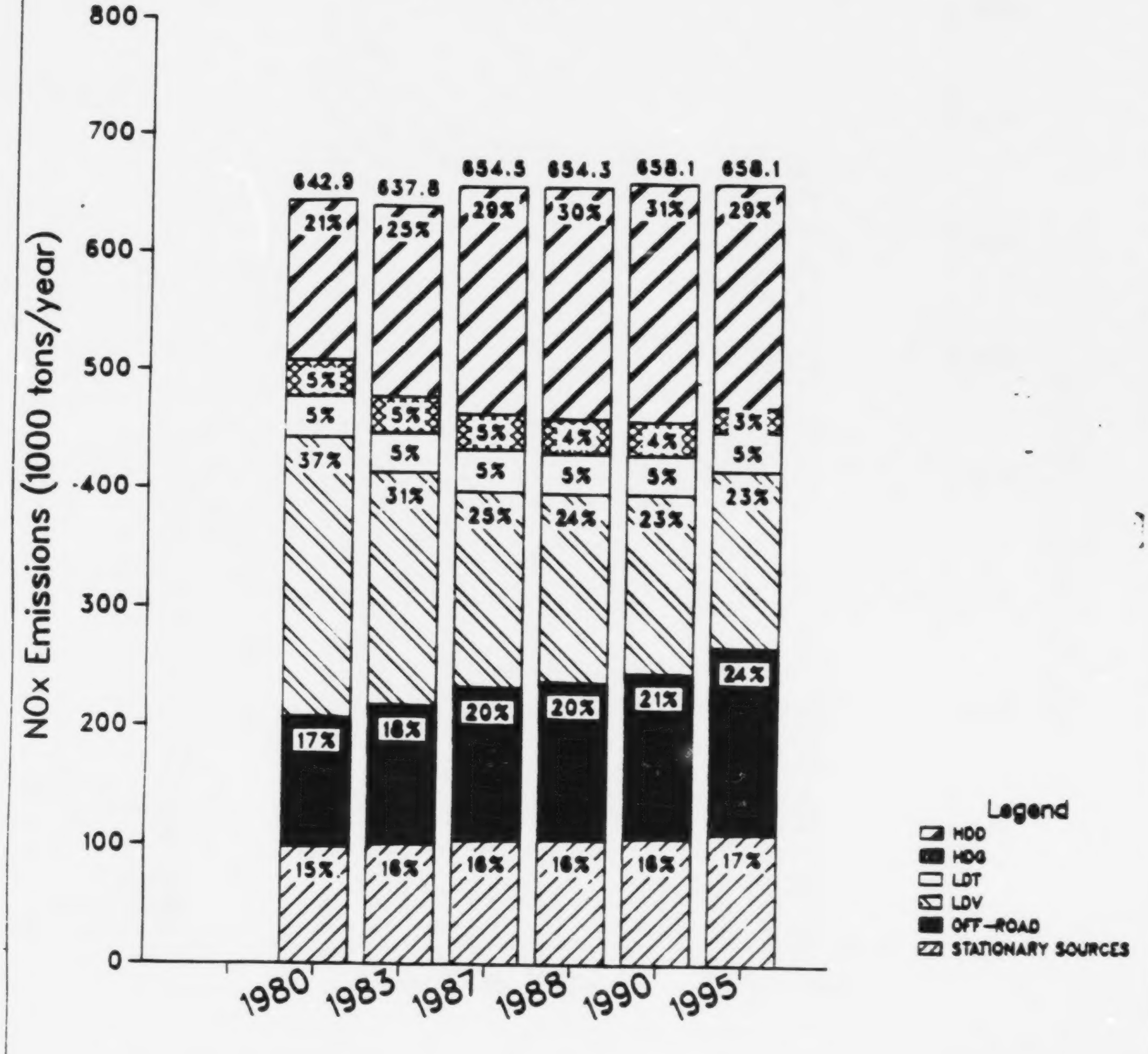


Figure 4-3
NOX EMISSIONS INVENTORY
HIGH NO2 URBAN AREAS
Statutory Case Projections
Low Altitude

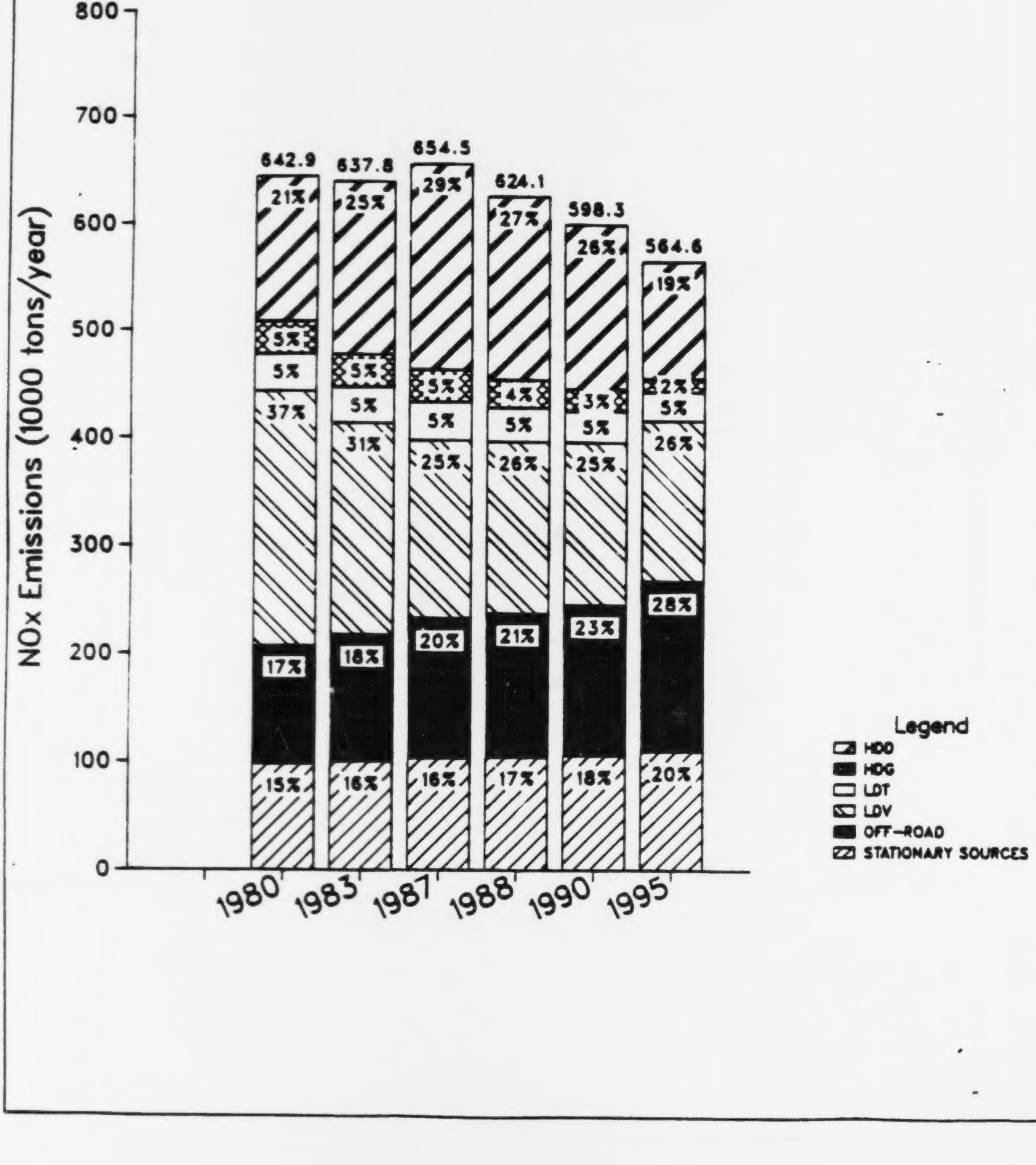


Figure 4-4
NOX EMISSIONS INVENTORY
HIGH NO2 URBAN AREAS
Base Case Projections
High Altitude

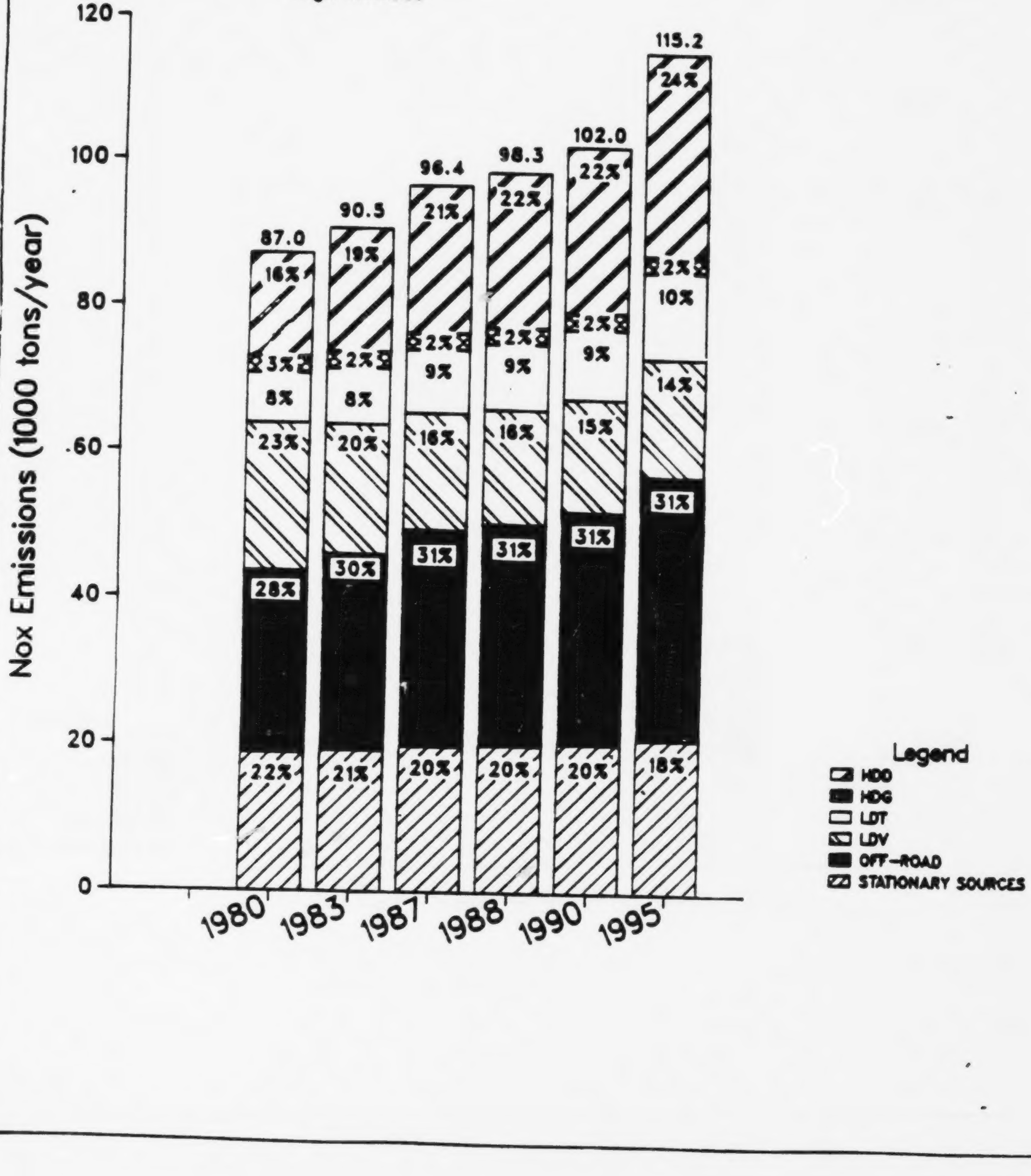


Figure 4-5
NOX EMISSIONS INVENTORY
HIGH NO2 URBAN AREAS
Controlled Case Projections
High Altitude

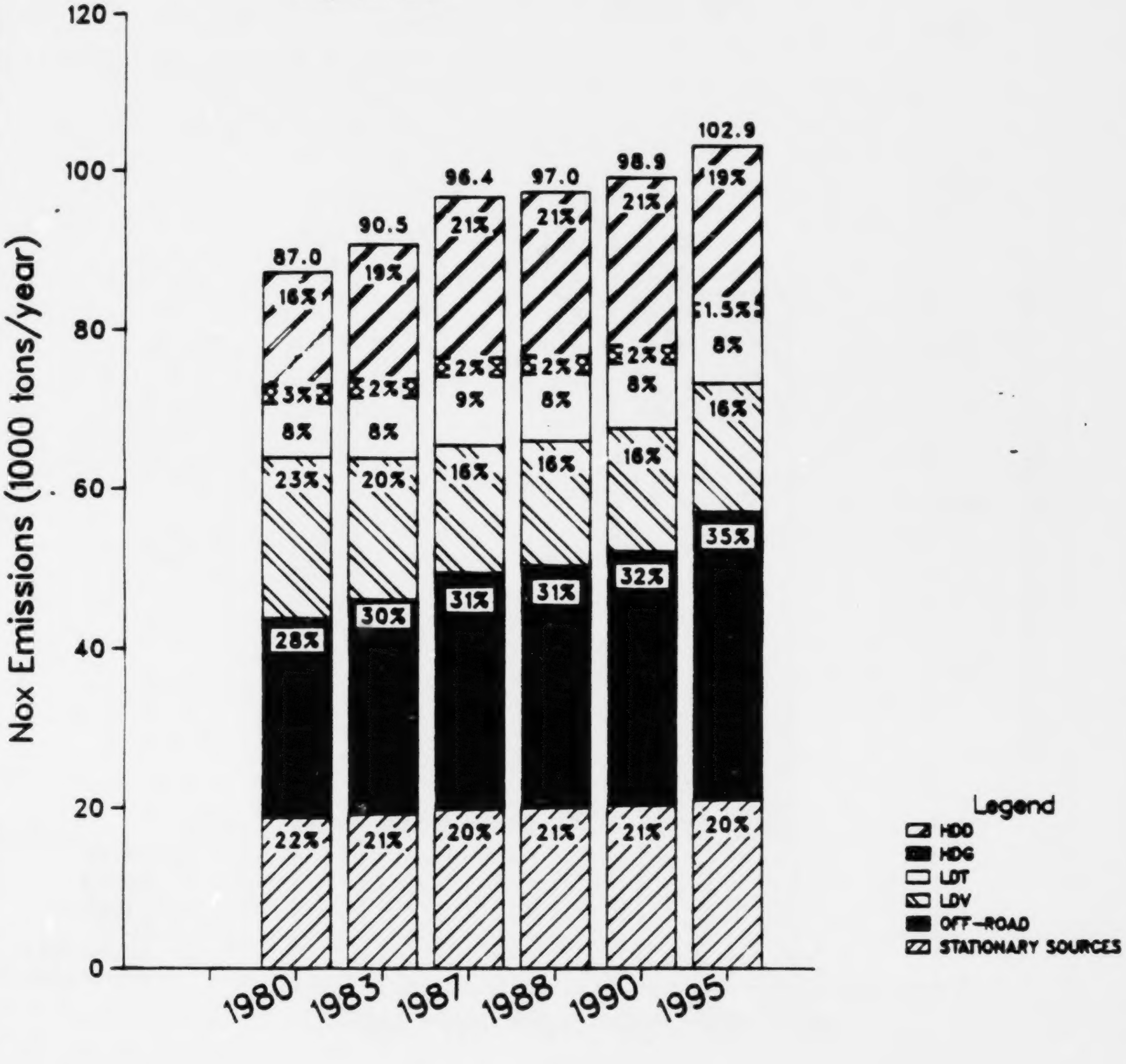


Figure 4-6

NOX EMISSIONS INVENTORY

HIGH NO2 URBAN AREAS

Statutory Case Projections
High Altitude

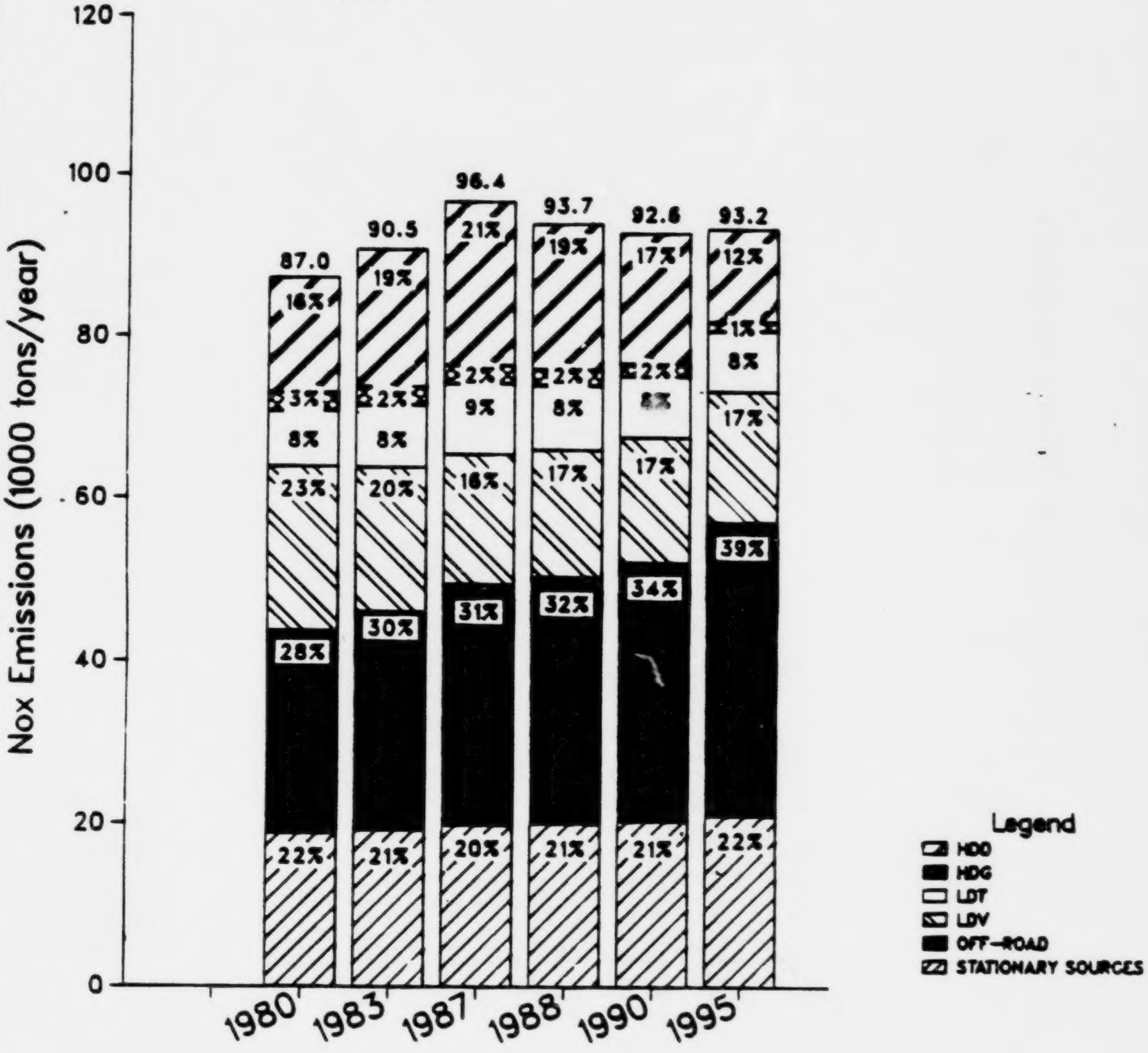


Figure 4-7

CHANGES IN CONTRIBUTION TO NOx INVENTORY

HIGH NO2 AREAS-LOW ALTITUDE

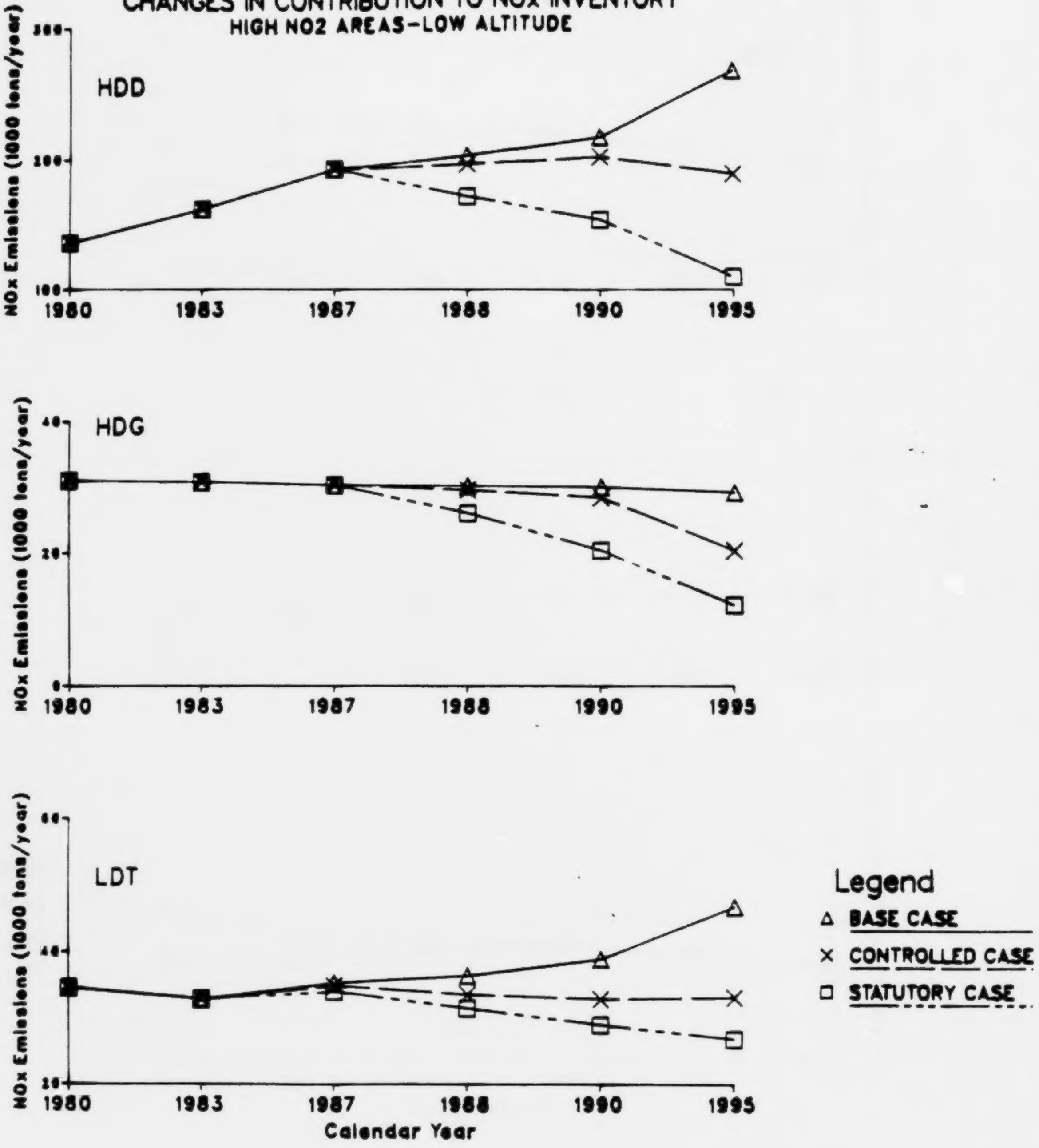
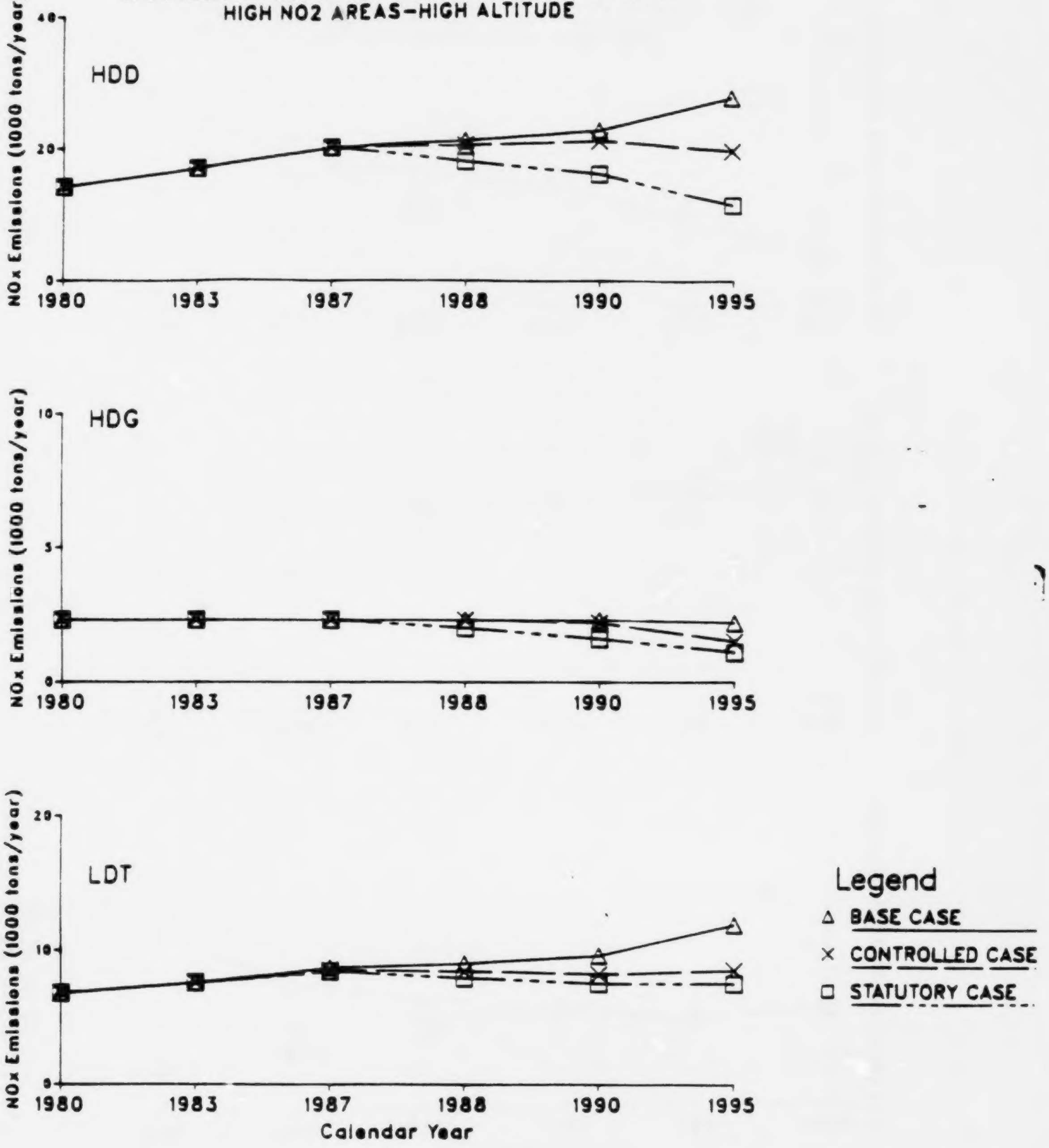


Figure 4-8
CHANGES IN CONTRIBUTION TO NOx INVENTORY
HIGH NO2 AREAS–HIGH ALTITUDE



these vehicles as reflected in the negative growth rate value in Table 4-6. HDDVs show the most significant increases in NOx contribution, both in absolute terms and on a percent basis by 1995, relative to current (1983) numbers. The increase is expected to be some 106,300 tons, or about a 66 percent growth. This increase is attributed to a projected substantial increase in the usage of diesel engines in HDVs. By way of additional illustration, Figure 4-7 also shows these inventory trends for the individual vehicle classes affected in this rulemaking.

b. Controlled Case

Figure 4-2 summarizes the total NOx inventory for the controlled-case projections in the six low-altitude areas, and Figure 4-7 shows the trends for individual vehicle classes. Because the new NOx standards are effective beginning with the 1987 model year LDTs and HDEs, with a further reduction for HDEs in 1990, only the 1990 and 1995 calendar years show significant changes relative to the base-case projections. As can be seen from comparing Figures 4-1 and 4-2, the sharp increase found in the uncontrolled inventory is almost completely eliminated under the controlled-case scenario. The total inventory increases by only about three percent between 1983 and 1995 for the controlled-case scenario, as compared to over 19 percent for the base-case scenario. The mobile source contribution to the total inventory decreases by 29,900 tons, or 7 percent, helping to offset the increases in the stationary source and off-road contributions, which are the same as in the base-case scenario. The 1995 LDT contribution to the NOx inventory declines by 29 percent, or 13,700 tons in absolute terms. About 20 percent of this reduction can be attributed to LDDTs, the remainder to LDGTs. The HDGV contribution decreases by 8,800 tons or 30 percent by 1995, although the percentage of total emissions is relatively small. The effect of introducing new NOx standards is most apparent for HDDVs, where the HDDV inventory is reduced by 79,000 tons in the 1995 calendar year, or almost 30 percent relative to the 1995 base case. Figure 4-2 also shows that by 1995 the HDDV class will constitute 29 percent of the total NOx inventory compared to 35 percent for the base-case inventory. The total controlled HDDV, HDGV, and LDT NOx contribution is about 37 percent of the total, versus 45 percent in the base case.

c. Statutory Case

Figure 4-3 represents the inventory reduction that could be achieved in the six low-altitude areas if the statutory standards were feasible from a practical standpoint for all vehicle classes. As can be seen, the total inventory would be reduced by 73,200 tons, or 11.5 percent. The mobile source inventory would be reduced by 123,400 tons (a 41.5 percent reduction) compared to the base-case, more than offsetting the abovementioned increase in the stationary source and off-road total. By 1995 the HDDV portion of the inventory would be reduced by 60 percent over the base case, a reduction of nearly 160,000 tons of pollutant on an absolute basis. HDGVs would show a 63 percent reduction in NOx production, or 19,000 tons on an absolute basis, while the LDT contribution would be reduced by 38 percent or 17,000 tons. Figure 4-7 illustrates these trends for each vehicle class. The total NOx inventory would be reduced not only from the 1995 base case (26 percent), but also from the 1980 base case (12 percent).

4. High-Altitude Emission Inventories

Figures 4-4, 4-5, and 4-6 present the base-case, controlled-case, and statutory-case NOx projections for non-California high-altitude SMSAs, and Figure 4-8 illustrates the trends for each vehicle class. Although the base- and controlled-case light- and heavy-duty gasoline vehicle NOx emission factors are lower than the corresponding low-altitude emission factors, the same trends are observed for the high-altitude emission inventories as were observed for the low-altitude results. The significant observations are a decrease in the growth of the total NOx inventory relative to the current (1983) level (from a 27 percent increase in the base-case scenario to less than a 14 percent increase under the controlled-case scenario), and also a reduction in the absolute and percentage contributions from LDVs, LDTs, and HDVs in the controlled-case emissions inventory relative to the base-case emissions inventory. The majority of the abovementioned increases in the total inventory under the controlled scenario comes from stationary source and off-road contributions, since the mobile source contribution would be only 1,300 tons, or about three percent over 1983 levels. A comparison of base-case and controlled-case combined LDT and HDV emissions shows that the 1995 controlled-case inventory contribution is about 30 percent lower than it would be under the base-case scenario for the comparable year. As can be seen from Figures 4-6 and 4-8, the statutory standards, if feasible, would result in a considerably greater reduction (52 percent) from uncontrolled levels, which would very nearly offset the increase in the stationary-source/off-road contribution.

5. Reductions in Total Emissions Resulting From the Proposed Standards

The environmental impact of imposing lower NOx standards on LDTs and HDVs has thus far been presented by examining the relative differences and trends between emission inventory projections as a function of time. It is also of value to examine in more detail the emission inventory impact of the new NOx standards at a point in time after the implementation of the new standards.

Tables 4-7 and 4-8 summarize the differences between the 1995 base-case and the 1995 controlled-case projections for low- and high-altitude areas, respectively. These results were calculated from the emission inventory data used to prepare Figures 4-1 through 4-6. Tables 4-7 and 4-8 express the NOx reduction in tons, as a percent reduction of the respective vehicle class inventory, and as a percent reduction of the total NOx inventory.

These tables clearly demonstrate the relative significance of the LDT, HDGV and HDDV contributions to the total NOx inventory. For example, at low altitude HDDV emissions comprise 79,000 tons out of a total NOx reduction of 103,600 tons, or a reduction of 10.4 percent of the total inventory, and at high altitude, 8,200 of 12,600 tons total reduction, or 7.1 percent of the total NOx inventory. The total inventory decreases by 13,700 tons or 1.8 percent at low altitude due to the LDT NOx reduction, and by 3,400 tons or 3 percent at high altitude. The HDGV reduction is 8,800 tons at low altitude and 700 tons at high altitude, which are 1.2 and 0.6 percent respectively of the total motor vehicle inventories.

6. Sensitivity to Alternative Design Values

Emission inventory and air quality projections are based on many assumptions and judgments concerning the input parameters used for analysis. The average annual NO_2 concentrations, or design values, mentioned earlier constitute one of the basic inputs to the analysis. Recent EPA guidelines suggest that alternative design values be included in such analyses to insure the results would not be unduly biased by unrepresentative high or low concentrations for a given year. Therefore, inventories and air quality calculations for this analysis were performed using both 1980 and 1981 design value data.

The results presented in Figures 4-1 through 4-8, which are calculated using 1980 as the base year, were reanalyzed using 1981 base year projections. The net results were very slight decreases in the emission inventories for particular emission classes and in the total inventory. For example, using 1981 design values results in projections of total NO_2 emissions that are 1.5 and 1.3 percent lower than those using 1980 design values, for the 1995 base- and controlled-cases,

Table 4-7

1995 Incremental Reduction in NO_2 Emission Inventories for High NO_2 SMSAs--Low Altitude

Vehicle Class	Reduction from Base Case Reduction (x1000 tons)	Percent of Respective Vehicle Class Emissions	Percent of Total Emissions
	Controlled Case		
Heavy-Duty Diesel	79.0	29.5	10.4
Heavy-Duty Gas	8.8	30.1	1.2
All Light-Duty Trucks	13.7	29.3	1.8
Total LDT, HDE	103.6	30.1	13.6
	Statutory Case		
Heavy-Duty Diesel	158.0	59.0	20.8
Heavy-Duty Gas	17.0	58.2	2.2
All Light-duty Trucks	20.0	42.7	2.6
Total LDT, HDE	195.0	56.7	25.7

---

[1] 1980 base year inventories.

Table 4-8

1995 Incremental Reduction in NO_2 Emission Inventories for High NO_2 SMSAs--High Altitude

	Reduction from Base Case		
Vehicle Class	Reduction (x1000 tons)	Percent of Respective Vehicle Class Emissions	Percent of Total Emissions
	Controlled Case		
Heavy-Duty Diesel	8.2	29.3	7.1
Heavy-Duty Gas	0.7	31.8	0.6
All Light-Duty Trucks	3.4	28.6	3.0
Total LDT, HDE	12.6	29.9	10.9
	Statutory Case		
Heavy-Duty Diesel	11.5	59.8	10.0
Heavy-Duty Gas	1.1	50.0	1.0
All Light-Duty Trucks	4.4	37.0	3.8
Total LDT, HDE	17.0	40.4	14.8

---

[1] 1980 base year inventories.

respectively. Similar changes were observed when the high-altitude projections were calculated using 1981 as the base year: 1995 base- and controlled-case inventory projections decreased 2.3 and 2.1 percent, respectively. In all cases, the differences between the 1981 and 1980 design value analyses inventories were within 3 percent, which is well within the uncertainty of the rollback model's projections.

Because the NOx emission reductions were calculated using a 1980 base year, the incremental tonnage reductions in Tables 4-7 and 4-8 will also change slightly when the analysis is made using 1981 as the base year. However, the magnitude of these changes are again within the uncertainty of the rollback model's assumptions. EPA, therefore, feels confident that the benefits attributed to the new standards are reasonable estimates and are not sensitive to small changes in the design values.

D. Air Quality Effects

The air quality effects of imposing new NOx standards may be determined by examining the results obtained from the EPA Rollback Model. Tables 4-9 through 4-12 present projections of the number of National Ambient Air Quality Standard (NAAQS) exceedances for NO_2 and the average percent change in ambient NO_2 concentration relative to a base year. The tables are organized according to location (either low altitude or high altitude), control scenarios, and design values. Base-case, controlled-case, and statutory-case projections are presented for both 1980 and 1981 design values.

Tables 4-9 and 4-10 quantify the effects of enacting new LDT and HDE NOx standards in terms of the number of high NO_2 urban areas which are predicted to exceed the NAAQS for NO_2. In the base case, the effect of the steady increase in total NOx emissions over time is shown to adversely affect NAAQS attainment, especially in the 1990s. The number of NO_2 exceedances in this time frame is significantly decreased by enacting new LDT and HDE NOx standards. Using the 1980 design value results, the number of low-altitude exceedances is reduced from three to one in 1995. Within the accuracy of the model, this reduction appears to hold true whether the proposed or the statutory standards are implemented. At high altitude, on the other hand, where the 1995 exceedances are reduced from two to one by the proposed standards, the statutory standard results in no exceedances in 1995.*

---

* It should be pointed out that although only three of the six low-altitude SMSA's are projected to exceed the NAAQS in 1995 without new truck standards, two of the three remaining areas studied which are currently below the standard are projected to be at the standard by 1995.

Table 4-9

Number of SMSAs Exceeding the NO_2 Ambient Air Quality Standard

Low Altitude

	1983	1987	1988	1990	1995
Base Case:					
1980 Design Value	1	1	1	1	3
1981 Design Value	0	0	0	1	2
Controlled Case:					
1980 Design Value	1	1	1	1	1
1981 Design Value	0	0	0	0	0
Statutory Case:					
1980 Design Value	1	1	1	1	1
1981 Design Value	0	0	0	0	0

Table 4-10

Number of SMSAs Exceeding the NO_2 Ambient Air Quality Standard

High Altitude

	1983	1987	1988	1990	1995
Base Case:					
1980 Design Value	0	1	1	1	2
1981 Design Value	0	0	0	0	2
Controlled Case:					
1980 Design Value	0	1	1	1	1
1981 Design Value	0	0	0	0	0
Statutory Case:					
1980 Design Value	0	1	0	0	0
1981 Design Value	0	0	0	0	0

Table 4-11

Average Percent Change in the Ambient NO_2 Concentration from the Base Year[1]

Low Altitude

	1983	1987	1988	1990	1995
Base Case:					
1980 Design Value	-1	2	4	7	19
1981 Design Value	-1	1	2	5	17
Controlled Case:					
1980 Design Value	-1	2	2	2	3
1981 Design Value	-1	1	1	2	1
Statutory Case:					
1980 Design Value	-1	2	-3	-7	-12
1981 Design Value	-1	1	-3	-7	-12

---

[1] Negative value means a decrease in ambient concentration. Positive value means an increase in ambient concentration.

Table 4-12

Average Percent Change in the Ambient NO_2 Concentration from the Base Year[1]

High Altitude

	1983	1987	1988	1990	1995
Base Case:					
1980 Design Value	5	14	16	21	37
1981 Design Value	3	12	14	17	35
Controlled Case:					
1980 Design Value	5	14	14	16	20
1981 Design Value	3	12	12	14	17
Statutory Case:					
1980 Design Value	5	12	8	7	5
1981 Design Value	3	12	8	6	3

---

[1] Negative value means a decrease in ambient concentration. Positive value means an increase in ambient concentration.

The EPA rollback model also calculates the average ambient air quality change expected for a particular set of NOx standards. Tables 4-11 and 4-12 present the average percent change in NOx air quality. Again, the low and high altitude results are presented for the base-case, controlled-case, and statutory-case scenarios and as a function of the design value year.

An analysis of Tables 4-11 and 4-12 produces the same general observations as described for Tables 4-9 and 4-10. Significant improvements in average ambient air quality are apparent when comparing the base- and controlled-case concentration changes. For example, the low-altitude average increase in NO_2 concentrations from 1983-1995 is 20 percent (from -1 percent to +19 percent of the 1980 value), calculated using the base-case/1980 design values. The corresponding 1983-1995 controlled-case projection shows a 4 percent increase in average NO_2 concentration or a difference of 16 percent due to the implementation of the proposed standards. The statutory case would yield an 11 percent decrease in ambient NO_2 concentrations if it could be implemented. In high altitude areas, the average increase in NO_2 concentrations from 1983-95 drops from 32 percent under the base-case scenario to 15 percent under the controlled case scenario. This represents an improvement of 17 percent due to the proposed standards. The statutory standards would result in no increase in NO_2 concentrations in 1995 relative to 1983.

Breaking down the differences in NO_2 concentrations resulting from the proposed standards by vehicle class, 13 percent of the abovementioned 16 percent differences in NO_2 concentrations at low altitude is due to the reduction in HDDV NOx emissions. In the high altitude areas, 13 percent of the 17 percent total difference in NO_2 concentrations is attributable to the HDDV NOx reduction. LDGTs, LDDTs, and HDGVs each account for about one percent of the difference.

As in the case of emission inventory calculations, air quality projections are also affected by changes in the design values. Using 1981 design values results in slightly different air quality projections from those listed above, which can be used to provide a sensitivity analysis for the calculations. In general, using 1981 design values results in fewer projected NAAQS exceedances and slightly lower projected NO_2 concentrations than result from using 1980 design values. However, the relative differences between the base-case and controlled-case projections remain almost the same. For example, implementation of the proposed standards results in a reduction in the number of low-altitude areas exceeding the NO_2 NAAQS from three to one in 1995 using the 1980 design values. Using the 1981 design values results in a reduction due to the proposed standards from two exceedances to zero in 1995. Thus, the effect of implementing the proposed standards is the same in either instance-1995 NO_2 violations are reduced by two. In high altitude areas, the number of exceedances is reduced by two under the 1980 design values and by one if the 1981 values are used.

Similar air quality improvements are observed between 1983 and 1995 when examining the low-altitude base- and controlled-case ambient NO_2 concentration projections using 1981 design values. The average percent increases in NO_2 concentrations during the period 1983-95 are projected to be 18 percent and 2 percent for the base-case and controlled-case scenarios, respectively. Thus the average decrease in low altitude NO_2 concentrations under the proposed standards would be the same when calculated using 1981 design values as it would using 1980 values, (i.e., 16 percent). In high altitude areas, the average increase in NO_2 concentrations between 1983 and 1995 under the proposed standards would be 15 percent using 1981 design values, as opposed to 17 percent using the 1980 values. The base case increase would be 32 percent for either design value. Under the statutory standards, the high altitude NO_2 concentrations would peak in 1987 and decline to 1983 levels by 1995, using either design values. Low-altitude statutory-case concentrations would decrease 11 percent under either set of design values.

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CHAPTER 5

PARTICULATE ENVIRONMENTAL IMPACT

I. Introduction

This chapter will briefly examine the air quality impact of the proposed particulate standards for heavy-duty diesel trucks. In addition, four classes of health and welfare effects will be considered: 1) non-cancer health effects, 2) carcinogenic health effects, 3) visibility effects, and 4) soiling effects. For a more in-depth presentation of the environmental effects associated with diesel particulate control, the reader is referred to EPA's Diesel Particulate Study (DPS).[1]

It should be noted that the two control scenarios considered in this chapter differ somewhat from those presented in the DPS report. The effects described in that study were adjusted for the difference in standards for inclusion in this chapter, using the ratio of the respective emission inventories as described in the sensitivity analysis chapter of the DPS report. Since the effects models are essentially linear, no significant inaccuracy should result from this adjustment.

II. Particulate Control Scenarios

Environmental effects will be presented for two basic control scenarios. In the base-case scenario heavy-duty diesel engine (HDDE) particulate emissions would remain at the uncontrolled level, approximately 0.7 g/BHP-hr. The controlled-case scenario assumes the implementation of a particulate standard of 0.60 g/BHP-hr effective for the 1987-89 model years, followed by a more stringent standard of 0.25 g/BHP-hr effective for the 1990 and later model years. Proportional standards of 0.72 and 0.30 g/BHP-hr are also being proposed, effective in the 1987 and 1990 model years, respectively, for HDDE particulate emissions under high-altitude conditions.

III. Air Quality Impact of Diesel Particulate Control

This section will assess the effects of the proposed standards on localized, urban, and nationwide air quality in order to provide a basis for assessing health and welfare benefits. The section will include: 1) a discussion of the relationship of diesel particulate to total suspended particulate emissions and a discussion of the applicable air quality standards, 2) a discussion of particulate emission factors, or average vehicle emission rates, for the above HDDE control scenarios and the resultant lifetime emissions per vehicle, 3) a discussion of HDDE particulate emissions relative to those from other sources, 4) the resulting effect of the proposed standards on localized, urban, and national atmospheric concentrations, and 5) a discussion of particulate emissions in high-altitude areas.

A. Relationship of Diesel Particulate to Total Suspended Particulate and the National Ambient Air Quality Standards

Total suspended particulate (TSP) matter includes all particles entrained in the air. As such, it includes large particles like dust and dirt, as well as small particles like soot, and chemical elements such as lead, antimony, arsenic, etc. TSP can be subdivided according to size into three broad categories: coarse, inhalable, and fine. Fine particulate has diameters of less than 2.5 micrometers (um) and, because of its small size, almost all diesel particles fall into this category. At the same time, inhalable particulate, generally referred to as PM_{10}, has diameters of less than 10 um. Again, because of its small size, diesel particles are all classifiable as inhalable particulate.

There have been National Ambient Air Quality Standards (NAAQS) for TSP since 1971. A primary NAAQS for TSP of 75 micrograms per cubic meter (ug/m^3) on an annual geometric mean basis, or 260 ug/m^3 within any 24-hour period (which may not be exceeded more than once each year), has been set to protect public health. A more restrictive secondary standard of 150 ug/m^3 (24 hour short term) was set to protect public welfare (i.e., other items of value such as materials, crops, etc.) against any known or anticipated adverse effects.[2]

EPA will soon propose a primary NAAQS for PM_{10} in the range of 50-65 ug/m^3 (annual arithmetic mean basis) in place of the current primary TSP standard. Inhalable particulate is estimated to comprise 46-55 percent or more of TSP on a nationwide average.[3] Some 71-246 counties are currently projected to violate the PM_{10} NAAQS, depending on the level of the standard. By 1995, numerous violations of the suggested NAAQS are still projected to occur, despite best efforts at controlling non-mobile sources of inhalable particulate. Because diesel particulate is all inhalable, the control of HDDVs is germane to attaining and maintaining any PM_{10} NAAQS. Thus, comparisons of the effect of diesel particulate controls will be made in the following sections with respect to the PM_{10} standards being considered.

EPA has not as yet determined a need for a secondary PM_{10} standard, though a secondary fine particulate standard has been considered for visibility protection. If a secondary NAAQS is established, a comparison of the effect of diesel particulate controls would also be directly relevant to such a standard because almost all diesel particulate is fine.

B. HDDV Emission Factors and Resultant Lifetime Emissions Per Vehicle

Emission factors represent the average emission rates, expressed in grams per mile, for each pollutant under various standards. They are calculated for various classes and subclasses of vehicles based on data accumulated through emissions testing. Emission factors for future model years are estimates developed from historical emissions data using standard modeling techniques.

The derivation of the HDDV particulate emission factors presented in this chapter is described in the DPS report and will not be repeated here.[1] It should be noted, however, that the rates shown in the table below differ from those presented in the DPS report in three ways. First, the standards differ from the scenarios in the DPS report, resulting in slightly different emission rates. Second, in the DPS report, emission factors changed slightly for each model year, reflecting projected improvements in engine/vehicle operating efficiencies. In this chapter, a single emission rate was selected to be reasonably representative of the model years included in each scenario. This action greatly simplified the analysis with no significant effect on the results. Third, the emission factors are given as a composite factor for all HDDVs, while those in the DPS report were presented for three HDDV subcategories. This change was made to simplify the analysis in this chapter and to focus the analysis on the entire HDDV class, which is the object of control. The composite factor was derived by weighting the individual emission based on the lifetime mileage for each respective vehicle category, (i.e., 110,000 for LHDDVs, 268,000 for MHDDVs, and 529,000 for HHDDVs) and their respective sales fractions (33 percent for LHDDVs, 25 percent for MHDDVs, and 42 percent for HHDVs). The following table presents average emission rates for the base-case and the controlled-case scenarios for the entire class of HDDVs:

Average Emission Rates (g/mi)

Scenarios	HDDV
Uncontrolled	2.1765
Controlled	
0.60 g/BHP-hr (1987)	1.8656
0.25 g/BHP-hr (1990)	0.9325

It should also be noted that these emission rates do not explicitly include any adjustment for the higher emissions of HDDVs at high altitude. As explained later, very little data are available with which to evaluate this emissions increase. Also, because the above rates are used to characterize emissions on a national basis and HDDV VMT at higher altitude is very small compared to that at low altitude, the effect of not specifically including an adjustment for vehicles at higher elevations is negligible. Therefore, not explicitly considering the higher emission rates for high-altitude HDDVs has an insignificant effect on the results of this analysis.

The average emission rates can now be used to determine total lifetime emissions per vehicle for comparison of base-case and controlled-case levels. The average emission rate is multiplied by the average estimated lifetime mileage for HDDVs. The following table presents the base-case and controlled-case lifetime HDDV particulate emission levels resulting from the proposed 1987 and 1990 standards. The estimated lifetime mileage used in the calculation is also shown. This mileage was derived from a sales-weighting of the lifetime mileages mentioned above.

Standard	Lifetime Emissions (tons) Per Vehicle HDDV
Uncontrolled	0.78
Controlled	
0.60 g/BHP-hr (1987)	0.67
0.25 g/BHP-hr (1990)	0.34
(Estimated Lifetime Mileage)	(325,480)

C. HDDV Particulate Emissions Inventory and Comparison to Other Sources

Now that the emission factors and lifetime emissions per-vehicle have been described, total HDDV particulate emissions can be determined for various future years. This shows how the HDDV particulate emissions inventory changes with time, including how the various standards affect emissions, and allows for comparisons with other sources.

The methodology used in determining total particulate emissions is contained in the DPS report. This methodology will not be repeated here. Note, however, that the scenarios in this chapter are slightly different from those in that study, so the inventory contributions were recalculated using the emission factors developed for this analysis. The figures presented here reflect EPA's best estimate of diesel sales through 1995. This sales estimate is also described in the DPS report.

Table 5-1 presents the projected HDDV, LDDV, and LDDT contributions to the 1995 mobile source urban emissions inventory. Urban areas are of primary interest since diesels have the greatest effect on these locations, and since the great majority of people in PM_{10} non-attainment areas reside in urban locations. The table includes the HDDV inventory contribution for both the proposed standards and a continuation of the 1987 standard of 0.6 g/BHP-hr to 1990 and beyond for comparison purposes. The light-duty motor vehicle contributions are also included for comparison purposes.[1] The LDDV and LDDT contributions are the same under the base-case and controlled-case scenarios and assume standards already in place (i.e., 0.2 and 0.26 g/mi, respectively, beginning in the 1987 model year). The 1995 LDDV and LDDT emissions increase substantially over 1983 levels because there were relatively few diesel vehicles in-use in 1983 in comparison to projected future numbers.

Table 5-1 shows that uncontrolled HDDVs were by far the major source of urban diesel particulate emissions in the past and that, if left uncontrolled, this relationship will continue. It is also apparent that without the proposed standards, the 1995 HDDV inventory will grow to nearly 90% more than the 1983 level.

This information is important with regard to the inhalable particulate NAAQS, which is currently being considered by EPA. It shows that HDDVs are by far the single most important mobile source contributor to urban violations of the suggested PM_{10} NAAQS. Moreover, it shows that any substantial reduction in

Table 5-1

1983 and 1995 Urban Diesel Particulate Emissions (tons)

	1983 Levels	1995 HDDV Scenarios		
		Base	Controlled (0.6)	Controlled 0.6/0.25
LDDV	6,400 (11%)*	21,700 (16%)	21,700 (18%)	21,700 (26%)
LDDT	1,500 (2%)	12,900 (10%)	12,900 (11%)	12,900 (15%)
HDDV	51,200 (87%)	97,000 (74%)	84,600 (71%)	48,600 (59%)
Total	59,100	131,600	119,200	83,200

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* Figures in parentheses indicate percent of total.

urban diesel particulate emissions would have to come from controlling HDDVs, since the LDDV and LDDT values in this table already reflect a significant degree of control. The proposed standards do provide a significant level of control, since with the standards the 1995 HDDV inventory would remain about 5 percent below the 1983 level (Table 5-1).

Looking specifically at the effects of the proposed 0.60 and 0.25 g/BHP-hr HDDV standards, Table 5-1 shows that the 0.6 standard in 1987 would not, by itself, prevent the substantial increase in HDDV particulate emissions from 1983 to 1995. With the addition of the 0.25 standard beginning in 1990, however, HDDV particulate emissions are essentially held constant from 1983 to 1995. Viewed another way, imposition of the 0.25 standard significantly offsets the projected increase in LDDV and LDDT particulate emissions. Therefore, the proposed 0.6 and 0.25 HDDV standards, in combination, are very effective in reducing the rate at which urban diesel particulate emissions are expected to grow.

D. Air Quality Projections for Urban Areas

The air quality and exposure estimates developed for the two control scenarios described above are presented in Table 5-2. The 1980 levels are included for comparison purposes. The 1995 estimates were adjusted as described above from the scenarios in the DPS report. The three major indicators of impact are: 1) ambient urban concentrations, which include a broad spectrum of city sizes and meterological conditions, 2) annual average urban exposures, which include a variety of individual activity pattern effects, based on exposures in four U.S. cities, and 3) microscale concentrations, which represent short-term (not over an hour) localized exposures.

The ambient urban concentrations of diesel particulate under the base-case scenario are projected to increase by about 160 percent from 1980 to 1995. The ambient concentrations resulting from this sharp increase can be placed in perspective by comparing them to levels of the PM_{10} NAAQS, which is currently being considered by EPA. In 1995 without the proposed HDDV standards, ambient urban particulate concentrations will rise to 1.6 to 7.8 ug/m^3, representing up to about 15 percent of the suggested NAAQS in large cities. This clearly can represent a significant portion of the NAAQS, especially in areas that are projected to be in continued violation of the PM_{10} standard. Under the controlled-case scenario, urban ambient diesel particulate concentrations will also rise from 1980 to 1995, but the increases will be significantly attenuated from those associated with the

Table 5-2

Effect of the Proposed Standards on Urban Air Quality

	Total Diesel Particulate Concentration (ug/m^3)-- LDDV, LDDT, HDDV		
		1995	
	1980	Base	Controlled
Ambient Urban Concentrations*			
City Population:			
Greater than 1,000,000	1.3-3.0	3.4-7.8	2.2-4.9
500,000 - 1,000,000	1.0-2.1	2.6-5.5	1.7-3.4
250,000 - 500,000	1.0-1.7	2.6-4.4	1.7-2.8
100,000 - 250,000	0.6-1.8	1.6-4.7	1.0-3.0
Annual Average Exposure to U.S. Urban Dwellers			
TOTAL	2.4	5.3	3.2
Microscale Concentrations			
Roadway Tunnel:			
Typical	57	106	65
Severe	145	270	166
Street Canyon:			
Typical	2	4	2
Severe	14	26	17
On Expressway:			
Typical	6	11	7
Severe	26	48	29
Beside Expressway	5	10	6

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* Ranges are average values plus and minus one standard deviation.

base-case scenario. The proposed HDDV standards will reduce the 1995 levels by about 40 percent to 1.0-4.9 ug/m^3. Therefore, the proposed standards can be important in reducing urban ambient particulate concentrations, which in turn, will help attain and maintain the suggested PM$_{10}$ NAAQS.

The estimates of annual average exposure for dwellers in urban areas increase from current levels of 2.4 ug/m^3 to 5.3 ug/m^3 by 1995 under the base-case scenario, or an increase of about 120 percent. The 1995 average drops to 3.2 ug/m^3 under the controlled-case scenario, representing an increase of about 55 percent over the 1980 average. Thus, the proposed standards would result in about a 40 percent improvement in average exposure to diesel particulates.

The third indicator of air quality, the microscale impacts, indicates the same trend. While these levels are well above the more regional, long-term figures, they are probably of less concern, due to the short-term periods involved and the lack of acute health effects associated with diesel particulate. However, these levels would be of concern for anyone spending long periods of time in such areas.

The three above indicators of air quality show decreases in air quality in future years regardless of the implementation of diesel particulate controls. However, the proposed standards will aid in mitigating this degradation and directly help in attaining and maintaining the PM$_{10}$ NAAQS which is currently under consideration.

E. High-Altitude Particulate Emissions

There are no available high-altitude particulate emission data for HDDVs, and the data for LDDVs tested in high-altitude areas are extremely limited. Such data as are available suggest that particulate emissions at high altitude may be as much as 50 percent higher than those from comparable vehicles operated at low altitude.[4] However, these data were from naturally aspirated light-duty engines. In contrast, most heavy-duty engines used in high-altitude areas are turbocharged. Since the boost pressure sensors, usually present on turbocharged engines, adjust for varying barometric pressures (i.e., altitude), EPA estimates that the current high-altitude increase in HDDV particulate levels should be lower than for light-duty vehicles, on the order of 20 percent. EPA has, therefore, set the high-altitude standards at 120 percent of the low-altitude figures.

The need for controls at high altitude should be apparent. Higher emission levels in high-altitude areas pose an even greater threat to the environment from a given number of vehicles than is found in low-altitude locations. As a case in point, Denver's "brown cloud" is an example of the type of visibility problem that could worsen considerably in the absence of control of diesel particulates. Denver is currently a non-attainment area for TSP, with a 1982 annual concentration as high as 173 ug/m^3 (annual geometric mean) and a short-term concentration of 510 ug/m^3 on a 24-hour basis (second highest reading). As stated earlier, some 46-55 percent of this TSP would likely be PM_{10}, placing this area well above the PM_{10} NAAQS currently under consideration. Recent studies have concluded that mobile sources are one of the three major contributors to the haze problem, and that they could become the major contributor if the current high rate of diesel sales continues.[5]

Given the present particulate emission levels, the Denver haze level could double by the year 2010. The more stringent 1987 LDDV and LDDT particulate standards will cut the increase in half, but this still results in a 50 percent deterioration in the visibility index. No quantitative study has been done at this time to gauge the effect of the proposed HDDV particulate standards in this particular problem. However, from the preceding discussion of mobile source inventory contributions, it appears that the HDDV contribution will be significantly greater than the LDD contribution in the coming years. The fact that the proposed standards are projected to reduce the HDDV lifetime particulate levels by about 50 percent by 1995 will therefore likely have a significant, beneficial effect on the problem. Denver is not the only high-altitude city experiencing air quality problems of this nature and the same conclusion can likely be drawn for other areas with similar problems.

IV. Health and Welfare Benefits of Controlling Diesel Particulate

As mentioned previously, the DPS report examined four aspects of the environmental impacts of diesel particulate: 1) non-cancer health effects, 2) carcinogenic health effects, 3) visibility, and 4) soiling.

A. Non-Cancer Health Effects

Particulate matter in general has long been regarded as hazardous to human health. EPA recognized this danger and established an NAAQS for total suspended particulate (TSP) as early as 1971. Currently, EPA is planning on revising the primary standard to focus on inhalable particles (i.e., those with diameters of 10 um or less (PM_{10})), because this fraction of total suspended particulate matter appears to be responsible for most of the human health effects associated with TSP.

As mentioned earlier, diesel particulates are all inhalable particulate, and nearly all of it can be classified as fine particulate (less than 2.5 um in diameter). Although a large body of data has been developed regarding the health effects of inhalable particulate matter, research limited specifically to diesel particulate is relatively new and somewhat inconclusive. An analysis of the available data indicates that, until more is known, diesel particulate generally should be regarded as being equivalent to other forms of inhalable particulate matter in terms of the hazard it presents to human health, although there is a possibility it may be somewhat more hazardous.[1] It should be pointed out, however, that even if regarded as posing the same hazard, diesel particulate is emitted directly into the breathing zone, rather than from tall stacks that would promote dispersion. Thus, the potential for human exposure is maximized.

Two basic concerns exist with respect to the health risk posed by inhalable particulate in general.[1] First, inhalable particulates are small enough so that they are not as readily prevented by the natural body defenses from reaching the lower respiratory tract, as would coarser particles. Fine particulate matter can penetrate to the alveoli, or deepest recesses of the lungs, where the oxygen-carbon dioxide exchange takes place with the circulatory system.[6] The body requires months or years to clear foreign matter from the alveolar region, as opposed to hours or days to clear the upper respiratory system. The second concern is that inhalable particulate may be composed of toxic materials or may have hazardous materials adsorbed onto its surface.

The most obvious non-cancer health effect of an inhalable particulate, such as diesel particulate, is injury to the surfaces of the respiratory system, which could result in reduced lung function, bronchitis or chronic respiratory symptoms. The hazardous chemicals that may be associated with particulate matter (e.g., organic compounds, lead, antimony, etc.) can either react with lung tissue or be transported to other parts of the body by the circulatory system. Particulate matter may also weaken the resistance of the body to infection and there are indications that it reacts adversely in conjunction with other atmospheric pollutants. For example, studies in London, New York, Buffalo, and Nashville have found an increase in the mortality rate, especially among older persons, when high particulate levels were accompanied by high sulfur dioxide levels.[7]

From the above discussion, it is clear that inhalable particulate matter (PM_{10}) has been linked directly with a myriad of adverse non-cancer health effects, and it is based on this information that EPA is proposing an NAAQS for PM_{10}. Also, diesel particles are all inhalable particulate and, therefore, can potentially cause the same health effects of concern. This relationship can be used to assess the overall benefits of controlling HDDV diesel particulate.

As stated previously, 71-246 counties are projected to be currently in violation of the range of primary PM_{10} standards being considered. Even after reasonable non-mobile source emission controls are implemented, numerous violations of the NAAQS are still projected to occur in 1995. Without the proposed HDDV standards, diesel particulate from these vehicles will account for about 1.6-7.8 ug/m^3 of the ambient particulate loading in urban areas, or up to about 15 percent of the suggested PM_{10} NAAQS. This clearly shows that HDDVs can be a significant source of inhalable particulate in urban areas. Imposition of the proposed HDDV standards would reduce this source's contribution to 1.0-4.9 ug/m^3, a reduction of up to about 40 percent. Therefore, the proposed HDDV standards can play an important part in in reducing urban PM_{10} concentrations. Furthermore, the resulting reduction in diesel particulate emissions within urban areas that continue to violate the suggested PM_{10} NAAQS, will directly reduce the non-cancer health effects associated with inhalable particulates in general.

B. Carcinogenic Health Effects

A number of studies have concluded that exposure to diesel particulate probably poses an additional risk of acquiring lung cancer. EPA surveyed these studies and developed scenario-specific risk factors for lung cancer incidence.[1] Table 5-3 shows the cancer risk estimates for both the base-case and the controlled-case scenarios presuming the compounds producing the cancer-risk are reduced in the same proportion as total diesel particulate. These estimates were again adjusted for differences in scenarios from those in the DPS, as described above. The estimated cancer risks from other selected causes are also shown for purposes of comparison.

The data indicate that while the risk of contracting lung cancer is greatest from smoking, exposure to diesel particulate may represent a significant portion of all non-smoking-related lung cancer. The upper limit of the uncontrolled scenario would represent six individuals in a million, or eight percent of all non-smoking-related lung cancer in the U.S. The lower limit still represents one in a million individuals, which has.

Table 5-3

Comparison of Risks from Various Sources

Sources of Risk	Estimated Annual Risk (risk/person-year)	Exposed Population
Commonplace Risks of Death		
Motor Vehicle Accident	222.0×10^{-6}	Entire U.S.
Drowning	26.0×10^{-6}	Entire U.S.
Burns	21.0×10^{-6}	Entire U.S.
Tornados, Floods, Lightning, Hurricanes, etc.	2.0×10^{-6}	Entire U.S.
Risks of Cancer Incidence		
Diesel Particulate (1995):		Urban U.S.
Base Scenario	$1.1 \times 10^{-6} - 6.1 \times 10^{-6}$	
Controlled Scenario	$0.8 \times 10^{-6} - 5.3 \times 10^{-6}$	
Natural Background Radiation (sea level)	20.0×10^{-6}	Entire U.S.
Average Diagnostic Medical X-Rays in the U.S.	20.0×10^{-6}	Widespread
Frequent Airline Passenger (4 hours per week flying)	10.0×10^{-6}	Limited
Four Tablespoons Peanut Butter Per Day (due to presence of aflatoxin)	8.0×10^{-6}	Fairly Widespread
Ethylene Dibromide	4.2×10^{-6}	Widespread
One 12-Ounce Diet Drink Per Day	2.6×10^{-6}	Widespread
Arsenic	1.7×10^{-6}	1% of U.S.
Miami or New Orleans Drinking Water (due to presence of chloroform)	1.0×10^{-6}	Southern U.S., Urban
Lung Cancers:		Entire U.S.
For Smokers Due to Smoking	419.0×10^{-6}	
For General Population Due to Causes Other Than Smoking	73.9×10^{-6}	

been used in the past by regulatory agencies as a cut-off point for determining the need to regulate. Thus, Table 5-3 shows that a relatively small but significant cancer risk may be attributable to diesel particulate exposures. The proposed HDDV standards would reduce this risk in 1995.

C. Visibility Effects

Reduced visibility is one of the more readily apparent effects of diesel particulate, as evidenced, for example, by Denver's "brown cloud" mentioned above. Diesel particulate reduces visibility by scattering and absorption of light. Diesel particles are of a diameter most effective in scattering light and their 65-80 percent carbon content produces a high degree of light absorption. The DPS developed a method for quantifying changes in visibility caused by changes in diesel particulate levels. The reader is referred to that study for a discussion of the methodology involved.[1]

Table 5-4 presents the estimated visibility impacts of the base- and controlled-case scenarios in terms of the average percent reduction due to diesel particulates in 1995 urban visibility from early 1970's baseline levels. The visibility figures were adjusted from those in the DPS report using the ratios of emission inventories as described above. Although the relationships between inventories and visibility is not exactly linear, the resulting error is neglible due to the low concentration of particles involved.

Table 5-4 shows that, in the absence of controls, increases in diesel particulate levels will result in decreases in visibility, ranging from a 21 percent decrease in largest cities, to 3-8 percent decreases for less populous urban areas. The proposed standards will cut the decrease to 14 percent in the largest cities, and to 2-5 percent in smaller urban areas. The controlled-case scenario thus offers a 1 to 7 percent improvement in visibility over the base-case scenario, depending on the size of the city. The lower limit of this impact (i.e., the effect for smaller cities), may not be perceptible. However, the effect for large cities would show a noticable improvement in visibility. The proposed standards, therefore, provide an overall benefit that would be most apparent in the areas where it was most needed.

D. Soiling Impacts

In a review of the scientific literature, the DPS found some evidence suggesting that because of its black color and oily nature, diesel particulate may have a disproportionate effect on soiling compared to the effect of other types of

Table 5-4

Average Reduction in Visibility
Due to Diesel Particulate in 1995
(percent reductions from base-year visibility)

City Size (population)	Base	Controlled
More than 1,000,000	21.1	14.1
500,000-1,000,000	7.7	4.9
250,000-500,000	5.5	3.2
100,00-250,000	3.1	1.9

particulate (i.e., diesel particulate would produce more soiling than TSP on a gram-for-gram basis). The black color may make the soiling more apparent to the observer and the oily nature may make it more difficult to clean. The net effect would be to increase costs to the general public for more frequent and more thorough cleaning events. However, because of the paucity of scientific data on the physical soiling effects of diesel particulate and TSP, no definitive statement of these relationships can be made at this time.

There is a somewhat larger body of literature available regarding the costs associated with various levels of soiling. A good summary of this economic literature can be found in an EPA report regarding the benefits associated with the proposed HDDV standards.[8] This report concludes that there are significant economic benefits to be gained from control of diesel particulates with respect to soiling.

E. Conclusions

Heavy-duty vehicles currently are the major source of diesel particulate emissions from mobile sources in urban areas. Unless controlled, the particulate emissions from this source are expected to nearly double by 1995. Such high levels can have a significant effect on ambient air quality in urban areas. Implementing the proposed standards will essentially hold the level of emissions from this source in 1995 at the 1983 level. The resulting reductions in ambient particulate concentrations will be beneficial in helping numerous areas meet the PM_{10} NAAQS currently under consideration by EPA. They will also produce benefits in terms of health effects, visibility, and soiling.

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CHAPTER 6

COST EFFECTIVENESS

I. Introduction

Cost effectiveness is a measure of the relative economic efficiency of an action toward achieving a specified goal. It is primarily useful in comparing alternative means of achieving that goal. The goal of the proposed regulations is to reduce particulate and NOx emissions, or perhaps more importantly, to reduce ambient levels of particulate and NOx in urban areas. In this chapter, the cost effectiveness of attaining this goal is expressed in terms of the dollar cost per ton of particulate or NOx emissions controlled.

More specifically, the primary purpose of this chapter is twofold: 1) to estimate the cost effectiveness of the proposed particulate standards for heavy-duty diesel vehicles (HDDV) and the proposed NOx standards for both light-duty trucks (LDT) and heavy-duty vehicles (HDV),* and 2) to compare these values to other mobile and non-mobile source control strategies. The cost effectiveness of the proposed HDDV particulate standards will be compared to the 1987 light-duty diesel motor vehicle (LDD) particulate standards and to selected stationary source controls. The cost effectiveness of the proposed NOx emission standards will be compared to light-duty gasoline and diesel vehicle (LDV) NOx controls and also to selected stationary source controls.

Another purpose of this chapter is to estimate the cost effectiveness of a particulate control scenario where separate, more stringent standards are proposed for urban buses. The analysis of this control scenario will be examined in Appendix I.

To determine cost effectiveness, two pieces of information are necessary: the costs and emissions reductions of the strategies to be examined. The measure of costs will be either the net present value of the purchase, operating, and maintenance costs, which accrue throughout the life of the vehicle, or an annualization of this lifetime cost. All the cost figures presented in this analysis are expressed in terms of 1984 dollars. The measure of emissions reductions will be either the lifetime emission reduction or the annual emission reduction. (Reasons for determining costs and benefits on either an annual or lifetime basis will be explained later.)

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* Standards are: HDDV particulate of 0.60 g/BHP-hr at low altitude and 0.72 g/BHP-hr at high altitude in 1987 and 0.25 g/BHP-hr at low altitude and 0.30 g/BHP-hr at high altitude in 1990; HDV NOx of 6.0 g/BHP-hr in 1987 and 4.0 g/BHP-hr in 1990; Class I LDT NOx of 1.2 g/mi in 1987; and Class IIA LDT NOx of 1.7 g/mi in 1987. The NOx standards apply to both diesel and gasoline vehicles.

Furthermore, for particulate, emission reductions will be determined on a total, inhalable, and fine basis.* The three classes of suspended particulate are examined in order to focus the analysis on the most important particulate matter with respect to public health and welfare. As discussed in Chapter 5, fine and inhalable particulate are of the greatest concern for public health because this material is deposited in the deepest, most sensitive portions of the lung. They also are very important because of their disproportionate effect on visibility. Total suspended particulate (TSP) is of concern because it includes not only fine and inhalable particles, but also coarser material that affects public welfare (i.e., soiling).

In addition, for particulate an attempt will be made to incorporate the relative air quality impact (per unit rate of emission) into the cost-effectiveness comparison.

The remainder of this chapter is divided into three major sections. The first section discusses the methodology for determining cost-effectiveness values for the proposed NOx and particulate standards. The second section estimates the cost effectiveness of the proposed particulate controls and compares them to the cost effectiveness of various mobile and stationary source particulate controls. The third section estimates the cost effectiveness of proposed NOx controls and compares them to the cost effectiveness of NOx control for other mobile and stationary sources.

II. Methodology

This section presents the two methods which will be used to estimate the cost effectiveness of the proposed NOx and particulate standards: the annual approach and the lifetime approach. To simplify the analysis somewhat, both methods evaluate the costs and emission reductions associated with an average vehicle on a per vehicle basis, rather than the total costs and benefits for the entire fleet.

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* Total particulate is all suspended particulate matter regardless of diameter, inhalable particulate is considered to be all particulate matter less than 10 micrometers in diameter, and fine particulate is considered to be all particulate matter less than 2.5 micrometers in diameter.

With the annual approach, costs are allocated: 1) to each year in which emission reductions were produced, and 2) in proportion to the size of these annual reductions. The result is a cost-effectiveness value which is applicable at any point in the life of a vehicle, as well as over the vehicle's entire lifetime. This approach will be used to evaluate both the proposed diesel particulate and NOx standards. This will allow comparisons on a consistent basis with recent EPA cost-effectiveness estimates for LDDV and light-duty diesel truck (LDDT) particulate controls, which were also computed using this method.[1] It will also allow comparisons of the proposed diesel particulate and NOx standards with stationary source controls, where cost-effectiveness values are typically determined on an annual basis.

With the lifetime approach, the lifetime costs are discounted to the year of vehicle purchase and then divided by the undiscounted lifetime emission reductions. The lifetime approach generally yields lower cost-effectiveness values relative to those produced by the annual approach. This is because the lifetime approach uses two different accounting techniques to assess costs and emission reductions. Costs are discounted, while benefits are undiscounted. The effect of this is that lifetime emissions reductions are higher than if they were discounted. On the other hand, the annual approach assesses both costs and emission reductions using a similar accounting technique (i.e., annualization) and, hence, are comparable. The lifetime approach will be used only in conjunction with the proposed NOx standards to allow comparisons with past LDV cost-effectiveness studies, where only this method was used.

In the remainder of this section, the derivation of cost effectiveness for both the annual and lifetime approaches will be presented. The discussion for each approach will progress from a general overview of the method, to a more specific discussion of the individual factors that are used in the cost-effectiveness equations.

A. Annual Approach

1. Derivation of Annual Cost Effectiveness

As described above, the annual approach allocates the cost of emission control: 1) to each year in which benefits were produced, and 2) in proportion to the size of these annual benefits.

The first step in this approach is to determine the net present value of the costs associated with the applicable standard which accrue throughout the vehicle's lifetime. More specifically, the net present value of the cost is the sum of the incremental purchase price and annual costs for changes in maintenance and operating expenses, discounted to the year in which the vehicle was purchased. In equation form, and assuming a conventional 10 percent discount rate evaluated during the mid-year,* this is expressed as:

$$NPV = X_1/(1.1)^{0.5} + X_2/(1.1)^{1.5} + X_3/(1.1)^{2.5} + \ldots X_i/(1.1)^{(i - 0.5)} \qquad (1)$$

Where:

NPV = net present value of vehicle's lifetime costs (including purchase, operating, and maintenance costs).

X_i = cost in year i (includes allocation of purchase, operating, and maintenance costs).

i = age (in years) of vehicle.

Equation 1 alone is not sufficient to determine the annual costs, however. The next step is to allocate the costs in proportion to the size of the annual emission reduction. For purposes of this study, this means that the annual costs are allocated in proportion to annual emission reductions, so that the cost effectiveness (annual costs divided by annual emission reductions) is the same for each year. In mathematical terms, this means:

$$CE_A = X_1/E_1 = X_2/E_2 = X_i/E_i \qquad (2)$$

Where:

CE_A = annualized cost effectiveness.

X_i = annual cost in year i.

E_i = annual emission reduction in year i.

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* The use of this discount rate has been discussed in Chapter 3. Evaluation is typically at the mid-year, which represents the average point in time of annual cash flow.

The annual emission reduction, E_i, is the average per-mile emission reduction multiplied by the average number of vehicle miles traveled (VMT) each year. This results in the following equation:

$$E_i = ER \times VMT_i \quad (3)$$

Where:

E_i = annual emission reduction in year i.

ER = average per-mile emission reduction.

VMT_i = VMT in year i.

Combining the above three equations leads to an equation where annualized cost-effectiveness values can be calculated. This equation is:

$$CE_A = NPV/[ER \sum_{i=1}^{n} VMT_i/(1.1)^{(i - 0.5)}] = NPV/[ER(SUM)] \quad (4)$$

The numerator in Equation 4 is the net present value of the lifetime costs associated with each proposed standard as derived in Chapter 3. These net present value costs will be presented later in this chapter when the particulate and NOx cost-effectiveness values are actually calculated.

The per-mile emission reduction for the proposed standards, which appear in the denominator of Equation 4, are based on emission rates that occur at the vehicle's half life (i.e., the average lifetime emission reduction). The use of average values assumes that the emission rate remains constant throughout the vehicle's lifetime. In reality, emissions tend to increase gradually with mileage. The use of average values slightly underestimates emission reductions early in life, and slightly overestimates them late in life. The overall effect on cost effectivenes is negligible, however, since these two competing emission trends essentially cancel one another and the deterioration rates for diesel particulate and NOx are small. Hence, average emission reductions can be used to simplify the analysis, without any significant effect on the results.

Also, using these average values allows direct use of the particulate and NOx emission results contained in Chapters 4 and 5, respectively. These emission results will be presented later when the cost-effectiveness values are calculated.

Unlike costs and emission reductions, the VMT summation (SUM) portion of the denominator in Equation 4 was not presented in an earlier chapter, and will be derived below.

2. Description of Annual VMT Estimates

The sum portion of Equation 4 requires that VMT be estimated for each year throughout the lifetime of the average vehicle. This study will attempt to estimate the annual VMT as actually incurred by motor vehicles. This differs slightly from EPA's cost-effectiveness analysis on diesel particulate emission control in the Diesel Particulate Study (DPS).[1] There, annual VMT was assumed to be constant throughout the lifetime of the vehicle. It was determined by dividing the estimated vehicle lifetime, in years, into the estimated lifetime VMT. However, the fact that most vehicles travel more during the first years and less during the latter years is ignored when using constant annual VMTs. The analysis in this chapter reflects the actual mileage accumulation for each year of operation. This should increase the accuracy of the estimates, since this is more representative of in-use experience.

Estimates of annual VMT by age are shown in Table 6-1 for LDVs,* LDTs, and the different weight classes of HDVs. These VMT values are derived by multiplying: 1) the average annual mileage accumulated for a vehicle with a lifetime of 20 years, and 2) the annual survival rate for a particular model year fleet. This manipulation accounts for the fact that as the model year fleet ages, some of the vehicles will be scrapped (i.e., annual VMT = 0). As will become clearer later, it is important to include this phenomenon in the VMT estimates because they are used to calculate the emission reductions for the fleet average vehicle. Unless the vehicles leaving the fleet are accounted for, the VMT for the fleet average vehicle will be overestimated, resulting in an accompanying overestimate of the emissions benefit. Therefore, the corrected VMT values are used to determine cost effectiveness rather than those for a surviving vehicle with a 20 year lifetime. The annual VMTs and survival rates were taken from a report by Energy and Environmental Analysis.[2]

Table 6-1 differs from that found in the EEA report[2] in two minor ways. First, no VMT are shown beyond 20 years of age, while the EEA report does present such values for LDTs and

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* Although LDVs are not affected by the rulemaking, their annual VMT estimates are included here. As already mentioned, the DPS assumed annual VMT was constant for this class of vehicle. To provide better comparison, the cost effectiveness from that study will be recalculated using varying annual VMT.

Table 6-1

Annual and Lifetime Average Per Vehicle VMT
(thousands of miles)

	Annual VMT					
Year	LDVs*	LDTs*	HDGVs	LHDDVs**	MHDDVs	HHDDVs
1	14.69	14.78	18.10	23.09	26.42	61.50
2	13.30	13.37	16.30	21.95	25.72	60.64
3	10.95	10.42	14.67	21.02	25.26	59.72
4	9.90	10.54	12.77	19.42	23.86	52.14
5	8.50	9.19	11.14	17.68	22.04	45.32
6	7.69	8.13	9.53	15.66	19.74	38.96
7	7.12	6.57	8.20	13.73	17.41	33.55
8	6.02	6.27	7.03	11.75	14.90	28.81
9	4.85	6.03	6.00	9.59	11.99	24.62
10	4.14	5.53	5.03	7.53	9.19	18.54
11	3.52	5.00	4.15	5.81	6.92	16.95
12	2.80	4.32	3.44	4.56	5.30	14.17
13	1.87	3.83	2.80	3.56	4.87	11.53
14	1.41	3.80	2.27	2.82	3.19	9.38
15	1.09	2.08	1.84	2.25	2.53	7.58
16	0.73	2.51	1.45	1.74	1.94	6.00
17	0.58	2.51	1.14	1.28	1.37	4.72
18	0.69	0.95	0.87	0.98	1.06	3.60
19	0.55	0.93	0.60	0.74	0.84	2.75
20	0.34	0.84	0.40	0.40	0.53	1.97
Total Lifetime VMT	100.74	117.78	127.73	179.80	215.16	502.65

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* Gasoline-fueled and diesel-fueled LDVs and LDTs have identical VMT distributions.

** Estimated by sales weighting Class IIb, III, and IV VMT using estimates from the EEA study.[2]

HDVs. The VMT beyond 20 years was discarded because it is negligible and simplifies the subsequent calculations. Second, EEA labels their HDV classes differently from EPA. The differences are shown below.

Heavy-Duty Groups as Classified by EPA and EEA

	Class IIB	Class III-V	Class VI	Classes VII & VIII
EEA	Trk 8.5-10	MDV	LHDV	HHDV
EPA	LHDV	LHDV	MHDV	HHDV

As can be seen, EEA and EPA similarly group vehicle classes, even though the descriptions differ for each group. The one exception is that EEA separates Classes IIB and III-V, while EPA combines them as LHDVs. In order to derive annual VMT for LHDVs, EEA's VMT estimates for Classes IIB and III-V were weighted according to the sales projection contained in Chapter 3.*

The lifetime VMT values in Table 6-1, which come from the EEA report[2], differ from independent EPA estimates.[1] The differences are highlighted below.

Lifetime VMT Estimates (in miles)

	LDVs	LDTs	HDGVs	LHDDV	MHDDV	HHDDV
EPA	100,000	120,000	110,000	110,000	268,000	529,000
EEA	100,700	117,800	127,700	179,800	215,600	502,600
Ratio EPA/EEA:	0.99	1.02	0.88	0.61	1.25	1.05

Note that, for LHDDVs and MHDDVs, the EPA and EEA lifetime VMT estimates differ significantly. In examining the EEA document, it appears that the VMT data for Class III-V vehicles (or LHDDVs under EPA labeling) are identical to VMT data for Class VI vehicles (MHDDVs under EPA labeling). This implies that EEA used an average VMT for both classes. Typically, the lifetime for Class III-V vehicles is much shorter than that for Class VI vehicles. The net effect of using an average VMT for both classes is to overestimate the lifetime VMT relative to EPA's LHDDV category, and to underestimate lifetime VMT for EPA's MHDDV category. Therefore, the difference between the EPA and EEA estimates for these two HDV categories seems to be readily explainable, and EPA's values appear to be better estimates.

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* It should also be mentioned that the HDGVs shown in Table 6-1 are a sales weighted average of EEA data for all heavy-duty gasoline vehicles. In the EEA report, the data were segregated into their respective vehicle classes.

In order to compensate for these differences, the EEA VMT values in Table 6-1 must be adjusted to reflect EPA's lifetime estimates. This is accomplished by simply multiplying each value in Table 6-1 by the ratio of lifetime VMT estimates for EPA and EEA. These adjusted values are shown in Table 6-1A and will be used in the subsequent cost-effectiveness calculations with one additional change. Rather than calculate individual cost-effectiveness estimates for LHDDVs, MHDDVs, and HHDDVs, the analysis can be greatly simplified by combining the VMTs for each of these classes into an average HDDV value for each year and for the vehicle's lifetime. These composite VMT values are found by sales-weighting the individual values. The HDDV sales fractions used to perform this conversion are: 33 percent for LHDDVs, 25 percent for MHDDVs, and 42 percent for HHDDVs. These values were previously estimated in Chapter 3.

Now that annual VMT values for LDDVs, LDDTs, HDGVs, and HDDVs have been described, the subsequent cost-effectiveness calculations can be simplified further by actually calculating the SUM portion of Equation 4 for each mobile source category. The resulting value for each vehicle category is shown below.

Summation of $VMT_i/(1.1)^{i-0.5}$ by Mobile Source Category

Category	Summation Value (thousands of miles)
LDVs	57.6
LDTs	72.8
HDGVs	71.5
HDDVs	211.2

These values will be used in the subsequent annual cost-effectiveness calculations.

3. Urban Cost Effectiveness (particulate only)

Thus far, the annual cost-effectiveness methodology considers nationwide emission reductions, without regard to geographic location. Since the great majority of people who are exposed to NAAQS violations for particulate matter live in urban areas, the control of diesel particulate in these areas

Table 6-1A

Annual and Lifetime Per Average Vehicle VMT (thousands of miles)

Year	LDVs*	LDTs*	HDGVs	LHDDVs**	MHDDVs	HHDDVs
1	14.58	15.06	15.59	13.79	31.46	64.72
2	13.20	13.72	14.04	13.01	30.62	62.82
3	10.87	10.62	12.63	12.46	30.08	62.85
4	9.83	10.74	11.00	11.61	28.41	54.87
5	8.44	9.36	9.69	10.48	26.24	47.70
6	7.63	8.28	8.21	9.28	23.50	41.00
7	7.07	6.69	7.06	8.14	20.73	25.31
8	5.98	6.39	6.05	6.97	17.74	20.32
9	4.81	6.14	5.17	5.79	14.28	25.91
10	4.11	5.63	4.33	4.46	10.94	19.51
11	3.49	5.09	3.57	3.44	8.24	17.84
12	2.78	4.40	2.96	2.70	6.31	14.91
13	1.86	3.90	2.41	2.11	5.80	12.13
14	1.40	3.87	1.96	1.78	3.80	9.87
15	1.08	2.12	1.68	1.33	3.01	7.98
15	0.72	2.56	1.25	1.03	2.31	5.31
17	0.58	2.56	0.98	0.76	1.63	4.97
18	0.68	0.97	0.75	0.68	1.26	3.79
19	0.55	0.95	0.52	0.44	1.00	2.89
20	0.34	0.85	0.34	0.24	0.63	2.07
Total Avg. Lifetime Miles	100.00	120.00	110.00	110.00	268.00	529.00

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* Gasoline-fueled and diesel-fueled LDVs and LDTs have identical VMT distributions.

** Estimated by sales weighting Class IIb, III, and IV VMT using estimates from the EEA study.[2]

should receive the greatest emphasis. This will be accomplished by allocating the costs of the proposed standards to the associated particulate reductions which occur only in urban areas.

The urban emission reductions are found by using annual urban VMT values in Equation 4, rather than annual nationwide VMT. Annual urban VMT for each mobile source category is simply the product of: 1) nationwide VMT for each year, and 2) the fraction of nationwide VMT that occurs in urban areas. The urban fraction for each mobile source category is: LDVs, 59.4 percent; LDTs, 48.8; and HDVs, 33.9 percent.[1] Other than this change, the annual approach is used as described earlier.

B. Lifetime Approach

Cost effectiveness using the lifetime approach is found simply by dividing the net present value of all costs that accrue during the life of the vehicle by the total lifetime emission reduction for the vehicle. That is, discounted costs divided by undiscounted emissions. Expressed mathematically, the lifetime cost-effectiveness value for each standard is determined by the following equation:

$$CE_L = NPV/(ER \times VMT_T)$$

Where:

CE_L = lifetime cost effectiveness.

NPV = net present value of lifetime costs.

ER = average per-mile emission reduction.

VMT_T = total lifetime VMT.

As described in Section II.A.1. of this chapter, the net present value of the lifetime costs used in the above equation is found by Equation 1. The lifetime costs were derived in Chapter 3 and will be presented later in this chapter when the lifetime cost-effectiveness values for NOx are actually calculated. The average per-mile emission reductions were discussed in Chapter 4 and will also be presented later when the NOx cost-effectiveness values are calculated. The lifetime VMT values were previously described in Section II.A.2. of this chapter. Specifically, they are: LDVs, 100,000 miles; LDTs, 120,000 miles; HDGVs, 110,000 miles: and HDDVs, 326,000 miles.

III. HDDV Particulate Cost Effectiveness and Comparisons to Other Sources

A. HDDV Particulate Control

This section will present the cost effectiveness of the 0.60 and 0.25 g/BHP-hr HDDV particulate standards, which are proposed to begin in the 1987 and 1990 model year, respectively. (Hereafter referred to as the 0.60 and 0.25 HDDV standards.) As explained before, a single cost-effectiveness value will be calculated using only the annual approach.

Table 6-2 summarizes the net present cost values and average per-mile emission reductions that are used in conjunction with Equation 4 to determine the annual cost effectiveness of the proposed HDDV standards. As discussed in Section II of this chapter, the cost information was taken from Chapter 3. The emission factor information was taken from Chapter 5. In addition, it should be noted that the costs and emission reductions for the 0.60 HDDV standard are the result of controlling an otherwise uncontrolled vehicle. For the 0.25 standard, however, these values are incremental to the costs and benefits that would result from supplementing the 0.60 HDDV.

The nationwide and urban cost-effectiveness values for each standard are presented in Table 6-3. Two interesting observations can be made based on the values in this table. First, the 0.60 standard is more cost effective than the 0.25 standard. This is not surprising since the benefits of each succeeding increment of pollution control normally is more costly to attain. In this case, the small reduction in particulate emissions under the 0.60 standard results from using inexpensive control technology. The larger reduction associated with the 0.25 standard is attained with relatively more expensive control techniques. Second, comparison of the nationwide to the urban cost-effectiveness values shows that, on an urban basis, the cost effectiveness of the standards is reduced (i.e., the cost per ton is higher). This is expected because the costs of a nationwide control program are allocated to a much smaller emission reduction (i.e., emission reductions outside urban areas are ignored).

Table 6-2

Costs and Emission Reductions for the Proposed HDDV Particulate Standards

0.60 g/BHP-hr (1987) Standard		
Average Discounted Costs* ($/vehicle):	Purchase Price	31
	Maintenance	0
	Fuel Economy	0
	Total	31
Average Emission Rates (g/mi)	Without Standard	2.1765
	With Standard	1.8656
	Reduction	0.3109
0.25 g/BHP-hr (1990) Standard		
Average Discounted Costs* ($/vehicle):	Purchase Price	424
	Maintenance	(32)
	Fuel Economy**	365-730
	Total	757-1,122
Average Emission Rates (g/mi)	Without Standard	1.8656
	With Standard	0.9323
	Reduction	0.9333

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* 1984 dollars discounted at 10 percent per annum to the year of vehicle purchase.

** One to 2 percent fuel penalty assumed.

Table 6-3

Cost Effectiveness of HDDV Particulate Standards ($/ton)*

	HDDV
Nationwide Cost Effectiveness:	
0.60 (1987) Standard	430
0.25 (1990) Standard**	3,500-5,200
Urban Cost Effectiveness:	
0.60 (1987) Standard	1,300
0.25 (1990) Standard**	10,000-15,000

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* One ton equals about 907,000 grams.

** Incremental cost effectiveness.

B. Comparison to Other Particulate Control Strategies

1. LDD Particulate Control Strategies

To gain an understanding of the relative efficiency of the proposed 0.60 and 0.25 HDDV particulate standards, their cost-effectiveness values can be compared to those for other mobile source particulate control strategies. This will be done by comparing the HDDV standards to the trap-oxidizer based LDD standards which are scheduled to become effective in the 1987 model year. These standards are 0.2 g/mi and 0.26 g/mi for light-duty diesel vehicles (LDDVs) and light-duty diesel trucks (LDDTs), respectively.

Cost-effectiveness values have already been estimated for the LDD particulate standards in the DPS report.[1] However, the cost-effectiveness values in that study assumed constant VMT for each year of the vehicle's life, and costs were alllocated simply by forming an annuity out of the net present coat values over the life to the vehicle. Therefore, to be comparable, these cost-effectiveness values must be revised using the methodology described in Section II of this chapter.

Table 6-4 contains the net present cost values and the per-mile emission reductions that are needed to complete the cost-effectiveness calculations. These values were derived using the methodology from the DPS report.[1] Table 6-4 also shows the revised LDD cost-effectiveness values.

Comparing Tables 6-3 and 6-4 shows that the proposed 0.60 HDDV standard is more cost effective than the LDD particulate standards. However, the reductions in particulate emissions under the 0.60 standard are not significant, as shown in Chapter 5. The proposed 0.25 HDDV standard appears to be somewhat more cost effective than the LDDV controls and about the same as LDDT controls on an urban basis. On a nationwide basis, the cost effectiveness of the 0.25 HDDV standard as it compares to that for LDDVs and LDDTs is just the opposite of that described for the urban basis.

2. Stationary Source Particulate Control Strategies

Another way of gauging the relative economic efficiency of controlling particulate emissons is to compare the cost effectiveness of the proposed HDDV particulate standards to the cost effectiveness of reducing particulate emissions from stationary sources. This comparson is presented in Table 6-5 on the basis of total, inhalable, and fine particulate. The eight stationary source values shown in this table were taken directly from the DPS report.[1]

Table 6-4

Cost Effectiveness Calculation for LDD Particulate Standards*

	LDDV	LDDT
Average Discounted Costs ($/vehicle)**		
1987 Standard	80-85	55-60
Average Emission Rates (g/mi)***		
Without 1987 Standard	0.420	0.403
With 1987 Standard	0.213	0.266
Difference	0.207	0.137
Nationwide Cost Effectiveness ($/ton)		
	$6,100-6,500	4,200-4,600
Urban Cost Effectiveness ($/ton)		
	$10,000-11,000	8,600-9,400

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* Based on the annual approach.

** 1983 dollars discounted at 10 percent per annum to the year of purchase.

*** 0.6 g/mi standard in effect for 1982-86; 0.2/0.26 g/mi standard in effect for LDDVs/LDDTs, respectively, for 1987 and beyond. NOx standards are assumed to be 1.0 g/mi for LDDVs and 1.2/1.7 g/mi for LDDTs.

Table 6-5

Cost Effectiveness Comparison
for Particulate Control of HDDVs
and Stationary Sources ($/ton)[1,2,3]

Source[4]	Particulate Size Basis Total	Inhalable	Fine
HDDV, 1987 Standard	430	430	430
Cement Kiln	1	840	1,800
HDDV, 1987 Standard (urban basis)	1,300	1,300	1,300
HDDV, 1990 Standard	4,400	4,400	4,400
HDDV, 1990 Standard (urban basis)	12,000	12,000	12,000
Kraft Smelt Tank	12,000	14,300	21,700
Electric Arc Furnace	9,500	14,900	15,000
Borax Fusing Furnace	13,300	17,500	19,700
Industrial Boiler	29,200	41,000	123,000
Kraft Recovery Furnace	32,400	41,400	59,000
Lime Kiln (baghouse)	47,200	58,100	90,800
Electric Utility	47,400	68,300	155,000
Lime Kiln (ESP)	75,700	94,400	152,000

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[1] Stationary sources are discounted to reflect their relative ground-level effect.

[2] 1983 dollars.

[3] For simplification, the midpoint of the ranges were used, where applicable

[4] Ranking based on inhalable particulate values. HDDVs are shown as a single source.

Before comparing the cost-effectiveness values in Table 6-5, two important points must be made. First, as discussed earlier, evaluating particulate emissions based on their size allows a better comparison of mobile and stationary source controls from a health and welfare perspective. Diesel particles are so small that they are almost all classified as fine particulate. Stationary source particulate is much more variable and included particles in all three size categories: total, inhalable, and fine. (Note that all fine particles are included in the inhalable fraction and that all fine and inhalable particles are included in the total.)

The control of inhalable and fine particulate is most important with respect to its effect on public health and fine particulate is solely important with respect to visibility. Coarser particles, which are included in the total category, are less important with respect to those two effects, but do play a role in soiling. Therefore, evaluating emission reductions on the basis of their size provides a better comparison among sources with regard to the most important health and welfare issues.

The second important point is that the stationary source cost-effectiveness values shown in Table 6-5 have been adjusted to reflect the relative air quality impact of those emissions (i.e., ground level impact) compared to that of diesel emissions. This provides a more relevant measure of environmental impact relative to population exposure, than if all emission reductions from stationary sources were compared directly to those for diesels.

However, it must be added that although this adjustment should increase the accuracy of the comparisons, it is still rough and the result is not an ideal comparison. Also, it still ignores the location of these ground level concentrations, particularly with respect to the number of people exposed and the local need for control (i.e., is the area in or out of compliance with the NAAQS). This may be a significant limitation since stationary sources can often be controlled on an individual basis (i.e., where the air quality problems occur), while mobile sources cannot. The use of urban cost-effectiveness values attempts to correct for this. Both urban and nationwide figures will be used here in comparison to stationary source figures as in some cases stationary sources are controlled on a nationwide basis and in some cases on a local basis.

The figures in Table 6-5 suggest that HDDV controls are quite favorable when compared to stationary source controls, regardless of the size of particulate examined or basis of control. Only the control of wet cement kilns appears to be more cost effective than any of the proposed HDDV standards. Thus, while this cost-effectiveness analysis is not able to take all pertinent factors into account, it can be concluded that there is no evidence that the proposed HDDV particulate standards are not cost effective with respect to stationary source controls, and in fact compare quite favorably.

IV. LDT and HDV NOx Cost Effectiveness and Comparisons to Other Control Strategies

A. LDT and HDV NOx Cost Effectiveness

This section will present the cost effectiveness of the proposed LDT and HDV NOx standards. The specific levels of these standards are 1.2 and 1.7 g/mi for light and heavy LDTs, respectively, beginning in the 1987 model year, 6.0 g/mi for HDVs beginning in the 1987 model year, and 4.0 g/mi for HDVs beginning in the 1990 model years. (Hereafter referred to as the 1.2/1.7 LDT, 6.0 HDV, and 4.0 HDV standards.) The cost effectiveness of proposed standards will be determined using the lifetime and annual methodologies, which were discussed in Section II.B. of this chapter.

A summary of the various costs and emission reductions associated with the proposed NOx controls is shown in Table 6-6. Separate cost-effectiveness values will be presented for the different fuel types within each vehicle class: LDGTs, LDDTs, HDGVs, and HDDVs. The cost figures in this table were previously developed in Chapter 3. The necessary emission factors were taken from Chapter 4, with two important changes. First, the NOx emission factors that are used in this analysis are a weighted average of the low- and high-altitude factors for each mobile source category. It is estimated that 97 percent and 3 percent of vehicles are driven at low and high altitudes, respectively. (NOx emission factors at low and high altitude differ only for gasoline vehicles.)

Second, the emission factors for LDGTs and LDDTs are sales-weighted averages for the light and heavy classes within each fuel type category. These composite emission factors were used because the costs from Chapter 3 were presented as an average of the two weight classes. The sales weighting here is also based on data contained in Chapter 3, which shows that the light and heavy fractions of the LDGT class account for about 51 and 49 percent of the sales, respectively. For LDDTs, the light and heavy fractions account for about 40 and 60 percent of the sales, respectively. Moreover, because any projected change in the sales mix is not expected to change the emission

Table 6-6

Costs and Emission Reductions for LDT and HDV NOx Standards

1.2/1.7/6.0 (1987) Standard

Average Discounted Costs* ($/vehicle)	LDGTs	LDDTs	HDGVs	HDDVs
Purchase Price	44-87	35	2	16
Maintenance	0	0	0	0
Fuel Economy**	0	0	0	0-730
Total Net Present Value	44-87	35	2	16-746
Average Emission Rates (g/mi)* **				
Without Standard	2.29	2.42	9.740	26.715
With Standard	1.25	1.63	8.477	22.385
Difference	1.04	0.79	1.263	4.330

4.0 (1990) Standard

Average Discounted Costs* ($/vehicle)	LDGTs	LDDTs	HDGVs	HDDVs
Purchase Price	N/A****	N/A	18	291
Maintenance			0	6
Fuel Economy**			0	0-730
Total Net Present Value			18	297-1,027
Average Emission Rates (g/mi)				
Without Standard	N/A	N/A	8.477	22.385
With Standard			5.660	14.950
Difference			2.817	7.435

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* 1984 dollars discounted at 10 percent per annum to the year of vehicle purchase.

** Assumes a 0-2 percent fuel economy penalty for HHDVs.

*** These emission rates differ somewhat from those in Chapter 4. An explanation of the changes is given in Chapter 7.

**** Not applicable.

factor significantly, it also is assumed to adequately characterize future sales.

Table 6-7 presents the resulting cost-effectiveness values for the proposed LDT and HDV NOx standards. Three interesting observations can be made based on the values in this table. First, the annual approach yields larger values than the lifetime approach, as would be expected. Second, the overall ranking of the proposed NOx controls from least to most cost effective is HDGV, HDDV, LDDT, and LDGT. Third, within the HDGV category and the HDDV catetory the cost effectiveness of the proposed 6.0 standard compared to the proposed 4.0 standards can be considered as being very similar, again given the uncertainty in the analysis.

B. Comparison to NOx Control Strategies for Other Mobile and Stationary Sources

As for the proposed particulate standards, the relative efficiency of the proposed LDT and HDV NOx standards can be determined by comparing their cost-effectiveness values to those for other mobile source control strategies. Information concerning the cost effectiveness for other mobile source strategies is limited to: 1) inspection and maintenance (I/M) for LDVs, and 2) the reduction in LDV NOx emissions from 1.0 g/mi to 0.4 g/mi.[6]

The cost effectiveness of these two strategies is shown in Table 6-8, along with the cost effectiveness of the proposed NOx standards. As can be seen, the proposed NOx standards are more cost effective, in all cases, than that shown for the other LDV controls.

Turning next to stationary source control, cost-effectiveness values were examined for four different emission sources utilizing different control technologies. These cost-effectiveness values were taken from a report by The Aerospace Corporation for the California Air Resources Board.[7]

The four sources examined by Aerospace were refinery heaters, industrial boilers, a CO boiler, and a glass furnace. Aerospace analyzed costs for various sizes and load factors in an attempt to cover the range of costs and benefits that would be representative of the four selected sources.

Table 6-7

Cost Effectiveness of
LDT and HDV NOx Standards ($/ton)

Cost Effectiveness	LDGTs	LDDTs	HDGVs	HDDVs*
1.2/1.7/6.0 (1987) Standard				
Lifetime Approach	320-630	340	15	10-480
Annual Approach	530-1,000	550	20	15-740
4.0 (1990) Standard**				
Lifetime Approach	N/A***	N/A	55	100-380
Annual Approach			80	170-590

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* The VMT factors used to calculate cost effectiveness are weighted averages for LHDDVs, MHDDVs, and HHDDVs, where the sales fraction is estimated at 0.30, 0.24, and 0.40, respectively of total HDD sales.

** Incremental cost effectiveness.

*** Not applicable.

Table 6-8

Lifetime Effectiveness Comparison of NOx Control for Mobile Sources

Source	Cost Effectiveness ($/ton)
HDGVs, 1987 Standard	15
HDGVs, 1990 Standard	55
HDDVs, 1990 Standard*	100-380
HDDVs, 1987 Standard*	10-480
LDDTs, 1987 Standard	340
LDGTs, 1987 Standard*	320-630
LDVs (1.0 to 0.4 g/mi)	2,400
LDVs (I/M)	2,500

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* Ranked according to midpoint of range.

Aerospace examined three different types of control technology for each of the four sources. The control technologies investigated include: 1) low NOx burners, 2) the selective noncatalytic reduction (SNCR) system, and 3) the selective catalytic reduction (SCR) system. Low NOx burners are widely used on utility and industrial boilers. The resulting NOx reductions are influenced by the burner configuration, type of fuel burned, and the type of combustion modification implemented prior to the use of the low NOx burner. The SNCR system can be applied primarily to industrial and utility boilers, CO boilers, and crude oil heaters. In SNCR control processes, ammonia is injected and reacts selectively with NO* at about 1,000°C, forming nitrogen and water. The SCR system operates in nearly the same fashion as the SNCR system, except that a base metal catalyst is used to lower combustion temperature. Aerospace also considered combinations of these three control technologies.

The cost effectiveness for each of the four stationary sources is shown in Table 6-9. The range in costs is due to different plant sizes, different operating load factors, and different control technologies applied to achieve a certain reduction in NOx emissions. These cost-effectiveness values were inflated from 1981 to 1983 dollars by 13.7 percent, based on the producer price index (PPI) for all industrial uses.[8]

Also shown in Table 6-9 are the cost-effectiveness values of both the proposed 1.2/1.7 LDT, and 4.0 and 6.0 HDV NOx standards. A comparison of these values with those for controlling stationary sources shows that the 1.2/1.7 LDDT standards and the 6.0 and 4.0 standards for HDGVs are more cost effective than any of the stationary source controls. For HDDVs and LDGTs, the range of cost-effectiveness values for the proposed standards and stationary source controls overlap in most cases, making specific comparisons more difficult. Generally, however, in most cases the cost effectiveness for HDDVs is better than that for the various stationary sources. For LDGTs, the cost effectiveness of the proposed NOx standards compares quite favorably to values for stationary sources.

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* Virtually all NOx emitted from stationary sources is in the form of nitric oxide (NO).

Table 6-9

Annual Cost-Effectiveness Comparisons for NOx Control of LDTs and HDVs and Stationary and Mobile Sources

Source*	Cost Effectiveness ($/ton)
HDGVs, 1987 Standard	20
HDGVs, 1990 Standard	80
HDDVs, 1987 Standard	15-740
HDDVs, 1990 Standard	170-590
LDDTs, 1987 Standard	550
Glass Furnace	430-700
LDGTs, 1987 Standard	530-1,000
CO Boiler	310-1,700
Refinery Heater	610-2,700
Industrial Boiler	660-11,000

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* Values ranked according to midpoint of range.

Overall, the cost effectiveness of the proposed NOx standards for LDTs and HDVs appears to be very good relative to that for stationary source controls. If the stationary source NOx emissions were discounted to reflect their relative ground level effect, as was done for particulate, the cost effectiveness of the proposed LDT and HDV NOx standard would compare even more favorably.

Of course, the same limitations that applied to comparison of particulate cost effectiveness has to be considered here as well. That is, the cost effectiveness comparisons do not account for the fact that stationary sources can often be controlled on an individual basis (i.e., where the air quality problems exist), while mobile sources cannot. Nevertheless, the available evidence indicates that controlling NOx from LDTs and HDVs is cost effective relative to controlling these pollutants from stationary sources.

V. Conclusion

The cost effectiveness of the proposed particulate and NOx standards appears to be favorable when compared with other mobile source control strategies. Also, despite some inherent difficulties in the comparisons with stationary sources, the cost effectiveness of the proposed particulate and NOx standards appears to be favorable. Therefore, based on the available information, the proposed standards appear to be a cost effective means of reducing particulate and NOx emissions compared to controlling these pollutants from other sources.

References

1. "Diesel Particulate Study," U.S. EPA, OAR, OMS, ECTD, SDSB.

2. "The Highway Fuel Consumption Model: Tenth Quarterly Report," Undated Draft, Energy and Environmental Analysis, Inc., Arlington, VA., 1983.

3. "Particulate Size Variation in Diesel Car Exhaust," Groblicki, P., and C. Begeman, SAE Paper No. 790421.

4. "Characterization of Diesel Exhaust Particulate Under Different Engine Load Conditions," Presented at the 71st Annual Meeting of APCA, Schrec, R., et al., June 25-30, 1978.

5. "Characterization of Particulate and Gaseous Emissions from Two Diesel Automobiles as Functions of Fuel and Driving Cycle," Hare, C. and T. Baines, SAE Paper No. 799424.

6. "Cost Effectiveness of Large Aircraft Engine Emission Controls--Final Report," U.S. EPA, OAR, OMS, ECTD, December 1979.

7. "Assessment of Simultaneous Use of NOx Control Systems on Stationary Sources in California," Vol. 1, The Aerospace Corporation, El Segundo, CA, February 1982.

8. "Economic Report of the President," (data gathered by the Bureau of Labor Statistics), February 1983.

APPENDIX A to Chapter 6

I. Introduction

This appendix contains the cost-effectiveness analysis of the proposed 0.10 g/BHP-hr diesel particulate standard for urban buses beginning in 1990. This standard is assumed to replace an existing standard of 0.60 g/BHP-hr, which is proposed to begin in 1987. Therefore, the cost effectiveness of the proposed 1990 standard is determined on an incremental basis.

II. Overall Methodology

Like HDDVs, the urban bus cost-effectiveness value will be determined on an annual basis. However, somewhat less data is available with which to characterize the urban bus fleet, so that the calculation of annual cost effectiveness is simplified.

The cost effectiveness determination will be made on a per vehicle basis by simply dividing the annual cost by the annual emission reduction for the average bus. Each of these factors is discussed separately in the following sections.

III. Annual Cost

The annual cost of the proposed particulate standard is found by annualizing the net present value (NPV) of the incremental purchase price, in addition to the incremental lifetime costs associated with maintenance and fuel economy. The net present value of these costs are estimated by EPA as follows.

Purchase price increment = $ 441
Maintenance increment = $ -12
Fuel economy increment = $1,750
Total NPV = $2,179

The purchase price and maintenance increments are assumed to be equivalent to those for MDDVs, as presented in Chapter 3. The fuel economy increment is based on an assumed two percent fuel economy penalty, 4.30 mpg base fuel economy, $1.20/gal fuel cost, 50,000 mi/yr travel, 10 year useful life, and a 10 percent discount rate.

The annual cost of the total NPV, over the 10 year life of the vehicle and at a 10 percent discount rate, is about $355.

IV. Annual Emission Reduction

The emission reduction is simply the difference in the average lifetime emission rates under the 0.6 and 0.1 g/BHP-hr standards, multiplied by the annual VMT. For urban buses annual VMT is assumed to be constant over the life of the average bus, i.e., 50,000 miles a year. The difference in the average lifetime emission rates, i.e., per-mile rates, for the two standards is found as follows.

$$\text{Emission Reduction}^* = \frac{(7.1\ \text{lb/gal fuel})(0.6-0.1\ \text{g/BHP-hr})}{(4.3\ \text{mi/gal fuel})(0.42\ \text{lb fuel/BHP-hr})}$$

$$= 1.966\ \text{g/mi}$$

Combining this average per-mile emission reduction and the yearly VMT, as described above, yields an annual emission benefit of 98,300 grams, or 0.108 tons per vehicle.

Note that unlike HDDVs, determining the emission benefit in this manner assumes that none of the requisite trap-oxidizers will fail. This assumption is based on the fact that urban buses undergo routine maintenance that will tend to remedy problems before failures result. Also, the operating regime of these vehicles is fairly narrow compared to HDDVs. This will allow manufacturers to better optimize the design and, hence, durability of trap-oxidizer systems. If the assumed "zero failure rate" proves to be overly optimistic, the cost effectiveness of the proposed standard would be reduced.

V. Cost Effectiveness

Now that the annual cost and emission benefit are known, the annual cost effectiveness of the 0.1 g/BHP-hr urban bus standard can be determined. This is simply the annualized cost (i.e., $355) divided by the annual emission reduction (i.e., 0.108 tons), or $3,300/ton.

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* The use of this equation to convert g/BHP-hr to g/mi is fully explained in the Diesel Particulate Study (DPS).[1]

References for Appendix A to Chapter 6

1. "Diesel Particulate Study," U.S. EPA, OAR, OMS, ECTD, SDSB.

CHAPTER 7

ALTERNATIVE ACTIONS

I. Introduction

In preparing a proposal for new standards, a wide variety of alternatives have been considered by EPA. The evaluation of alternatives is intended to identify the best approach available to EPA, and is an essential element of a Regulatory Impacts Analysis performed under Executive Order 12291.

This chapter will first of all briefly review the relevant statutory requirements facing the Agency under the Clean Air Act and the environmental needs being addressed by the proposal. Past actions by EPA which are directly relevant to the development and selection of options will then be identified. Following these introductory items, individual alternatives will be identified and analyzed.

II. Statutory Requirements

The Clean Air Act (the Act) provides specific direction concerning the control of both particulate and NOx emissions from mobile sources. Considering the control of particulate emissions first, Section 202(a)(3)(A)(iii) mandates the establishment of technology-forcing particulate emission standards for heavy-duty diesels beginning in 1981. These standards are to represent the greatest emission reduction achievable in the leadtime available while considering costs and other impacts. EPA had originally interpreted this provision as applying to both light- and heavy-duty diesels and initiated its efforts in the light-duty area. In subsequent litigation, the Court of Appeals restricted the application of Section 202(a)(3)(A)(iii) to heavy-duty diesels only, but upheld EPA's light-duty diesel standards based upon EPA's general regulatory authority contained in Section 202 (a)(1).

As for NOx control for heavy-duty engines, Section 202(a)(3) requires NOx standards to be implemented in 1985 which provide at least a 75 percent reduction from the baseline NOx level of gasoline-fueled heavy-duty engines. Recognizing the possibility of excessive cost or fuel economy impacts, the Act further provides for temporary revisions in these heavy-duty standards, for periods not to exceed three years, with subsequent standards always requiring additional emission reductions. EPA announced in 1981 (through its NOx ANPRM) its determination that the statutory NOx standard appeared infeasible for diesel engines and indicated that EPA planned to employ the revision provisions in its NOx standard-setting process.

The Act also provides the option to permanently change the level of the statutory (or final) NOx standard, either up or down, based upon study of the environmental effects of NOx emissions from heavy-duty vehicles. However, such permanent relaxation would have to be based upon a finding that there was no environmental need for further NOx control from heavy-duty engines, which is not feasible at this time.

Light-duty trucks are also included in this analysis. This is because some light-duty trucks are included in the Act's definition of heavy-duty vehicles. The Act includes as "heavy-duty" all vehicles having a gross vehicle weight greater than 6,000 lbs. On the other hand, EPA's light-duty truck class includes all trucks up to 8,500 lbs gross vehicle weight. Those light-duty trucks with gross vehicle weights between 6,001 and 8,500 lbs are considered heavy-duty for purposes of the Act, and thus are subject to the 75 percent reduction requirements discussed above. Light-duty trucks with gross vehicle weights under 6,000 lbs are being regulated under the general authority of Section 202(a)(1).

III. Environmental Need

To provide perspective on the alternatives selection and analysis process, the following paragraphs will briefly review some of the key results of the NOx and particulate environmental assessments from Chapters 4 (NOx) and 5 (particulate).

The analysis of Chapter 4 has shown that under current regulations, motor vehicle emissions constitute nearly two-thirds of the inventory in both 1980 and 1995, and they produce half of the net emissions growth in that period. However, NOx emissions from heavy-duty diesel engines, while already sizable in 1980, double by 1995 and overwhelm any expected reductions in other categories. Without the benefit of new regulation, overall NOx emissions are expected to grow about 20 percent between 1980 and 1995.

Currently, only one non-California region is in nonattainment of the NAAQS for NO_2, but this region has petitioned to have its status revised and attainment is expected to be granted soon. However, with the above growth in NOx emissions, five non-California regions are projected to be in non-compliance by 1995. In addition, increased NOx levels have a deleterious effect on ambient ozone concentrations, further aggravating the ozone attainment problem. Also, while NOx emissions are not the main focus with respect to the control of acid precipitation, they do contribute to the problem and any increases are undesirable.

In conclusion, further NOx controls are needed if attainment of the NAAQS for NO_2 is to be maintained. The goal of this control should at least be to maintain NOx emissions at their current levels.

Turning to particulate, the data in Chapter 5 have shown that without further control diesel particulate emissions will increase under any diesel growth scenario (i.e., diesel fraction of sales). However, the light-duty portion of the inventory is very dependent on sales and, with no increase in current diesel market penetration, would only be 10 percent of the total diesel particulate inventory.[1]

To put the air quality impact of these emissions into perspective, 71-246 counties are projected to be currently in violation of the range of possible standards for particulate matter under 10 micrometers in diameter (PM_{10}) which the Agency has proposed (49 FR 10408, March 20, 1984). The air quality impact of current diesel particulate emissions is about 1-3 ug/m^3 in urban areas, or roughly 2-5 percent of the potential PM_{10} standards. Under best estimate diesel growth, this impact will increase to about 2-8 ug/m^3, or a net increase of 1-5 ug/m^3 (2-10 percent of the potential PM_{10} standards), assuming the current 1987 LDD particulate standards are retained. However, even without this growth, numerous violations of the NAAQS are still projected to occur in 1995 even after the application of reasonable non-mobile source controls. Thus, additional particulate control from the mobile source area is desirable if PM_{10} attainment is to be a realistic goal.

Restricting growth in diesel particulate emissions is also important for a number of other reasons. One, diesel particulate is all inhalable and nearly all fine particulate, remaining suspended for long periods of time. Two, it is emitted at street level, directly into the breathing zone, maximizing its impact on ambient air quality. Three, there is a potential cancer risk associated with diesel particulate; the average annual risk to an urban dweller being 1 to 6 per million in 1995 with no further control. Four, due to its size and high carbon content, diesel particulate is very effective in reducing visibility; by 1995, reductions of 21 percent are projected in the largest U.S. cities and 3 to 8 percent in smaller cities. Five, due to its black color and oily nature, diesel particulate has the potential for a greater than average impact on soiling.

Overall, diesel particulate emissions will increase regardless of the growth scenario chosen and will aggravate an already serious ambient particulate problem. Cost-effective diesel controls will need to be applied to minimize this impact.

IV. Prior Related Actions

A proposal for heavy-duty diesel particulate control was published on January 7, 1981 (46 FR 1910). That notice proposed that a particulate emission standard of 0.25 grams per brake-horsepower hour (g/BHP-hr) be implemented for heavy-duty diesels in the 1986 model year. This standard was expected to require the application of particulate trap technology to heavy-duty diesels, similar in concept to traps being developed for light-duty diesels. The proposal also included appropriate test procedures for particulate sampling based upon the new EPA transient test requirement.

At about the same time, EPA published an ANPRM announcing its intent to promulgate revised NOx emission standards for heavy-duty engines and light-duty trucks (46 FR 5838, January 19, 1981). The standards discussed in the Advance Notice were 1.2 g/mi for light-duty trucks and 4.0 g/BHP-hr for heavy-duty engines. Strictly speaking, neither of these standards corresponded to the 75 percent reduction requirement of Section 202(a)(3)(A)(ii). The light-duty truck standard at that level would have been 0.9 g/mi, while the heavy-duty engine standard would have been 1.7 g/BHP-hr. As discussed in the ANPRM, the 1.2 g/mi standard was chosen to provide a standard of equal stringency to the existing 1.0 g/mi light-duty vehicle NOx standard, while the 4.0 g/BHP-hr standard was identified as the lowest standard applicable for heavy-duty diesels under the revision provisions of Section 202(a)(3)(B).

Today's proposal contemplates the use of emissions averaging to measure compliance with standards. EPA has previously evaluated averaging for particulate emissions from light-duty diesels, and has concluded that averaging can be used there to reduce the cost of complying with emission standards without significant environmental penalty. (For a full discussion of these issues, see 48 FR 33456, July 21, 1983). EPA has also previously announced that it was considering the adoption of an averaging program for NOx emissions from both heavy-duty engines and light-duty trucks (45 FR 79382, November 28, 1980).

V. Alternatives

Before examining specific alternatives, there are two general areas needing consideration. These are leadtime for new standards and emissions averaging.

It has already been noted that the Act specified the adoption of particulate standards for 1981 and NOx standards for 1985. In the case of particulates, the Administrator was to consider "the period necessary for compliance" in establishing what technology would be available for the model year to which the standards would apply. For NOx, leadtime was also to be considered, but in this case there were specific provisions calling for four years of leadtime.

Clearly, neither the 1981 date for particulate nor the 1985 date for NOx can be met at this time. For particulate, the Agency sees its task as that of implementing standards as soon as possible, while allowing necessary leadtime. For NOx, in light of the inability to meet the 1985 deadline, the Agency believes it appropriate to apply standards with less than four years of leadtime, in the interest of having them take effect as close to 1985 as possible. The criterion here is compliance with what EPA believes the intent of the leadtime provision to be, namely the provision of adequate time for compliance by manufacturers. If a standard were developed which was clearly feasible in less than four years, it would be inappropriate in the light of the 1985 requirement to delay its implementation beyond the period needed.

For heavy-duty engines, the analysis of technology indicates that some modest emission reductions are possible in the short term, but considerable time and effort will be required to obtain major reductions in emissions, particularly for heavy-duty diesel engines. Therefore, separate near-term and long-term possibilities have been examined. The goal of the near-term options is to implement a feasible degree of control as soon as possible, while the longer term standards are oriented toward attaining meaningful and needed emissions reductions. Considering the time required to complete the rulemaking process and technology considerations for manufacturers to respond to an initial standard, 1987 has been identified as the earliest year for a standard. Beyond that, 1990 has been identified as allowing time for implementation of more advanced technology.

Light-duty trucks present a different picture than heavy-duty engines in terms of leadtime. The technology for NOx control applicable to light-duty trucks has already been developed for passenger cars and will be easily adaptable to light-duty trucks. In fact, all the techniques expected to be used to meet new NOx standards are already being used on at least a portion of the light-duty truck fleet. In this situation, there is no need to look at short-term versus long-term standards. All of the options which have been considered are feasible in the short-term and are viewed here as options for 1987.

The topic of emissions averaging has been thoroughly examined through the earlier cited rulemaking to establish a light-duty diesel particulate averaging program. In brief, the flexibility of averaging is one way to improve the manufacturer's ability to comply with stringent standards. It increases the economic efficiency of the standards without decreasing the overall emission reductions they produce. Averaging for heavy-duty rather than light-duty involves the added complexity of two unique factors. These are the varying useful life periods to which different subcategories of heavy-duty diesel engines are certified and the difference steming from the use of g/BHP-hr as the units for heavy-duty engine emission standards, as opposed to the g/mi units applicable in the light-duty case. Both of these factors mean that different heavy-duty engines will have markedly different lifetime particulate emissions even though certified to the same standard. These two factors can, however, be dealt with through proper design of the averaging program. Therefore, averaging is considered below as an available option in connection with the more stringent standards (the 1990 standards).

The following sections will describe first the heavy-duty diesel particulate options, then the heavy-duty engine NOx options and lastly the light-duty truck options. The emphasis here will be on presentation of environmental and economic impacts of the options. For further discussion of the development process which led to the individual options selected for analysis refer to the Diesel Particulate Study[1]. The technology analysis of Chapter 2 of the Regulatory Impact Analysis also deals at length with the feasibility of the final 1987 and 1990 options.

A. Heavy-Duty Diesel Particulate

Eight options are presented for particulate control for HDDEs. These options and their key environmental and economic impacts are shown in Table 7-1. Options 1-5 progress in stringency, from least to greatest. Options 4A-4C are variations of Option 4; Options 4B and 4C being attempts to focus control in urban areas, where it is needed most. They split the HDDE class into two categories, imposing less stringent (and less costly) control on line-haul HDDEs which spend less than a quarter of their time in urban areas. The intended result is a more cost-effective program.

The first three options shown are based upon application of non-trap technology to heavy-duty diesel engines. Option 1, no further control, illustrates 1995 conditions if no standards are adopted. Given the increase in emissions between 1983 and 1995 which it represents, coupled with statutory requirements, this is not a viable option. Option 2 applies a 0.60 g/BHP-hr standard beginning in 1987. This represents a level which EPA believes feasible in the short term, without a large economic

Table 7-1

Chart of Key Facts for HDDE Particulate Control Options[1]

Option (g/BHP-hr)	1995 HDDE Emissions (tons/year)[2]	Reduction from Uncontrolled Emissions	1995 Total Mobile Source Emissions (tons/year)[2]	Type of Control System Required	Technical Difficulty	Cost Per Vehicle	Urban Cost Effectiveness ($/ton)
1. No Control	97,000 (90%)[3]	0%	131,600 (123%)[3]	None	None	--	--
2. 1987 - 0.60	84,600 (65%)	13%	119,200 (102%)	Non-Trap	Low	$ 31	1,300
3. 1987 - 0.60; 1990 - 0.40	63,100 (23%)	35%	97,700 (65%)	Non-Trap	High	195-390	4,000-8,000
4. 1987 - 0.60; 1990 - 0.25	48,600 (-5%)	50%	83,200 (41%)	100% Trap	High	917-1,282	13,000-18,000
4A. 1987 - 0.60; 1990 - 0.25 (w/Averaging (A))	48,600 (-5%)	50%	83,200 (41%)	70% Trap	High	757-1,122	10,000-15,000
4B. 1987 - 0.60; 1990 - 0.25(A) for Urban HDDEs; 1990 - 0.60 for line-haul HDDEs	63,600 (24%)	34%	98,200 (66%)	Urban: 70% Trap Other: Non-Trap	Moderately High Low	288-376	12,000-16,000
4C. 1987 - 0.60; 1990 - 0.25(A) for Urban HDDEs; 1990 - 0.40 for line-haul HDDEs	54,600 (7%)	39%	94,200 (59%)	Urban: 70% Trap Other: Non-Trap	Moderately High Moderately High	387-573	7,000-10,000
5. 1987 - 0.60; 1990 - 0.10	34,200 (-33%)	65%	68,800 (16%)	100% Trap	Very High	1,051-1,535	10,000-15,000

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[1] See Appendix A for description of procedures used to develop estimates of emissions, costs, and cost effectivenesses. Costs and cost-effectiveness values are incremental over Option 2 which is incremental over Option 1.

[2] Best estimate diesel sales assumed. Current 1987 PM standards assumed for LDDVs and LDDTs.

[3] Figures in parentheses indicate change from 1983 levels. 1983 Diesel PM Emissions: HDDE - 51,200, LDD - 7,900, Total - 59,100.

impact. While it deals with the need for control in 1987, it foregoes the opportunity to make use of available leadtime for a technology forcing 1990 standard. Thus, this option does not appear to satisfy the requirements of the Clean Air Act. Option 3 adds a technology forcing 0.40 g/BHP-hr standard in 1990. A significant reduction relative to uncontrolled levels would result from this option, while the need to develop trap technology would be avoided. On the other hand, emissions under this option would still increase from 1983 to 1995 and the 1990 standard could well turn out to eventually require the use of some traps.

Option 4 is a trap oriented option, with a 0.25 g/BHP-hr standard for 1990. Option 4A maintains the same standards as option 4, but applies particulate averaging for the 1990 standard. Both of these options would maintain 1995 heavy-duty diesel particulate emissions at or even slightly below 1983 levels. Option 4A would accomplish this result at substantially less cost and improved cost effectiveness than would option 4 because traps would only be needed on aproximately 70 percent of the fleet.

Options 4B and 4C have less stringent 1990 standards for line-haul engines, in recognition of the fact that these engines will spend much of their time in non-urban areas where the need for control is less. This avoids the need to deal with some of the most difficult trap applications although it should be noted that line-haul vehicles can most easily bear the cost since the cost of premium duty engines and line-haul vehicles is already high. Option 4C, with its more stringent 0.40 g/BHP-hr standard for line-haul applications, will maintain a focus on improved particulate control for line-haul diesel engines, which is important since extensive changes in engine technology are expected over the next decade.

Option 5 is the most stringent option considered. Traps would be required on all engines, increasing the benefits but also the technological risk. The potential for tampering with emission controls (i.e., removal of trap oxidizers) could also become a serious concern with this option since significant fuel economy penalties might be associated with some of the more difficult applications.

EPA's analysis of the pros and cons of all of the above options has led to the decision to propose Option 4A. An extended discussion of EPA's evaluation and the basis for the final choices has been prepared for the preamble to accompany the proposed rules, and will not be repeated here. EPA has chosen to put that presentation in the preamble rather than in this Regulatory Impact Analysis in order to make it available to the widest possible audience. For the convenience of the readers of this document, the preamble discussion is included as Appendix B to this chapter.

Briefly, Option 4A was selected because EPA believes traps to be feasible for heavy-duty diesel engines at a cost which yields cost effective control compared to other particulate control strategies. The line-haul option of Option 4C may also be desirable but, if so, it is not clear at this time. The 0.10 g/BHP-hr standard of Option 5 was not selected both because of the increased technological risk and because, although indicated in Table 7-1 to be of equal cost effectiveness to Option 4A, it is likely that Option 5 will actually have a higher (worse) cost effectiveness than will Option 4A.

B. Heavy-Duty Engine NOx

Four options exist for HDE NOx control, which are shown in Table 7-2 along with their key environmental and economic impacts. Urban control options are not presented due to the wider geographical nature of NO_2, ozone and acid rain problems.

Option 1 would adopt no new standards for heavy-duty engine NOx emissions. This option allows heavy-duty engine emissions to increase some 80 percent over 1980 levels without obtaining the cost-effective NOx control which is available. Option 1 also fails to satisfy the requirements of the Clean Air Act since it does not represent the maximum degree of reduction available for 1987.

Option 2 applies a 6.0 g/BHP-hr NOx standard beginning in 1987. This standard represents a technologically feasible and cost effective level for that year, but not for the later years. It would fail to make use of the available leadtime to produce technology-forcing standards for 1990.

Option 3 adds a 4.0 g/BHP-hr 1990 NOx standard to the 1987 standard of Option 2. Under this option, total 1995 NOx emissions will be held to within seven percent of 1980 levels. The most significant challenge in this option will be that of feasibility for heavy-duty diesel engines where substantial engine improvements will be required.

Option 3A is the same as Option 3 in all respects except for the addition of a NOx averaging program for heavy-duty engines. While it is likely that averaging would allow some cost savings and reduce the technical challenge of the 1990 4.0 g/BHP-hr standard somewhat, the benefits do not appear to be substantial and EPA has been unable to quantify any beneficial effects. This is unlike the case for particulates, where, for example, the ability to selectively apply traps is a clear benefit of averaging.

Table 7-2

Chart of Key Facts for HDE NOx Options[1]

Option (g/BHP-hr)	1995 HDE Emissions (tons/year)	Reduction from 1995 Base Case HDE Emissions	1995 Total NOx Emissions[2] (tons/year)	Technical Difficulty	Cost Per Vehicle	Cost Effectiveness ($/ton)[3]
1. 10.7 (No further control)	327,100 (80%)[4]	--	874,800 (20%)[4]	None	-	--
2. 1987: 6.0	286,200 (56%)	13%	833,900 (14%)	HDGE: Low HDDE: Low	$ 2 $16-746	15 10-480
3. 1987: 6.0 1990: 4.0	230,400 (26%)	30%	778,100 (7%)	HDGE: Moderate HDDE: High	18 297-1,027	55 100-380
3A. 1987: 6.0 1990: 4.0 (Averaging)	230,400 (26%)	30%	778,100 (7%)	Improved over 3	Improved over 3	Improved over 3

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[1] See Appendix A for descriptions of procedures used to develop estimates of emissions, costs, and cost effectivenesses. Cost and cost-effectiveness values are incremental relative to the previous option.

[2] Assumes 1995 non-HDE NOx emissions of 547,700 (i.e., no further control).

[3] Based upon lifetime cost approach

[4] Figures in parentheses indicate increase over 1980 levels. 1980 NOx Emissions: HDE - 183,000, Total - 729,900

EPA has chosen to propose Option 3 for heavy-duty engine NOx standards. Analogous to the approach described above for particulate options, EPA has formulated its discussion of the analysis and selection process leading to the form of the proposal for inclusion in the preamble to the NPRM. That discussion is included as part of Appendix B to this chapter. In summary, Option 3 provides significant cost effective reductions in heavy-duty engine NOx emissions not obtained through Options 1 or 2. Averaging, on the other hand, does not have a clear enough benefit to argue for Option 3A at this time.

C. Light-Duty Truck NOx

Six 1987 control options are presented for controlling LDT NOx emissions. These are shown in Table 7-3. Options 1 and 2 represent traditional LDT standards, applying to the entire class. Options 2A and 2B relax the 1.2 g/mi standard to 1.7 g/mi for either all (Option 2A) or just diesel-powered (Option 2B) heavier LDTs (those above 3,999 lbs equivalent test weight (ETW) or above 6,000 lbs GVW; referred to as LDT_2s). (These weight cut-offs are the same as those used by California and/or the Act in determining vehicle classes.) Option 2C is the same as Option 2 for all LDTs except heavier diesel-powered LDTs where the existing standard (2.3 g/mi) would apply. Finally, Option 3 is simply labeled "averaging" and applies to any of the previous three options.

Option 1 represents a continuation of current standards for all light-duty trucks and would require a finding, for the heavier trucks in this class, that more stringent standards are environmentally unnecessary. As noted in Chapter 4, although their contribution is growing, NOx emissions from light-duty trucks are a relatively small portion of the total urban NOx inventrory. With the tighter standards in place for light-duty vehicles and the proposed heavy-duty standards, more stringent NOx standards for light-duty vehicles may not be needed to help achieve and maintain attainment of the NO_2 National Ambient Air Quality Standard (NAAQS) until the middle or late 1990s. This raises the possibility that more stringent LDT NOx standards could be delayed and implemented sometime after 1987. It may also be possible to achieve similar reductions from other sources at a lower cost. Nevertheless, there may be environmental benefits associated with LDT NOx emission reductions beyond the issue of NAAQS attainment (e.g., acid rain).

Option 2 would establish a 1.2 g/mi standard for all light-duty trucks. In the Advance Notice for NOx standards (46 FR 5838, January 19, 1981) a 1.2 g/mi light-duty truck standard was derived by EPA as equivalent in stringency to the 1.0 g/mi

Table 7-3

Chart of Key Facts for LDT NOx Options[1]

Option (g/mi)	1995 LDT NOx Emissions (tons/year)	Reduction From 1995 Base Case LDT Emissions	1995 Total NOx Emissions (tons/year)[2]	Technical Difficulty	Cost per Vehicle	Cost Effectiveness ($/ton)[3]
1. 2.3	58,700 (42%)[4]	--	747,200 (2%)[4]	Low	--	--
2. 1.2	39,200 (-5%)	33%	727,700 (0%)	Moderate Low	LDDT:$50-78[7] LDGT: 66-109[7]	350-550 460-760
2A. LDT_1: 1.2[5] LDT_2: 1.7	41,600 (0%)	29%	730,100 (0%)	Low	LDDT: 35 LDGT: 44-87	340 320-630
2B. LDT_1: 1.2 $LDGT_2$: 1.2 $LDDT_2$: 1.7	39,300 (-5%)[6]	33%	727,800 (0%)	Low	LDDT: 35 LDGT: 66-109	340 460-760
2C. LDT_1:1.2 $LDGT_2$:1.2 $LDDT_2$:2.3	40,000 (-3%)[6]	32%	728,500 (0%)	Low	LDDT: 10 LDGT: 66-109[7]	210 460-760
3. Averaging	Same	Same	Same	Same	Improved	Improved

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[1] See Appendix A for descriptions of procedures used to develop estimates of emissions, costs, and cost effectivenesses.

[2] Assumes 1995 non-LDT NOx emissions remain constant at 1980 levels (688,500).

[3] Based upon lifetime cost approach

[4] Figures in parentheses indicate increase over 1980 levels. 1980 NOx Emissions: LDT - 41,400, Total - 729,900.

[5] LDT_1: All LDTs at or below 3,999 lbs ETW or 6,000 lbs GVW.
LDT_2: All LDTs above 4,000 lbs ETW and 6,000 lbs GVW.

[6] This inventory is likely to be higher than indicated here. The model used to calculate the inventory figure assumes a lower percentage of $LDDT_2$s for 1995 than is currently anticipated.

[7] Includes the effects of a one percent penalty in fuel economy for LDT_2s at 1.2 g/mi.

light-duty vehicle NOx standard. EPA still believes this to be the case. This standard thus represents a measure of equity between NOx control for light-duty vehicles and light-duty trucks. As discussed in the Advance Notice, EPA also views a 1.2 g/mi standard as satisfying the intent of the 75 percent reduction requirement of the Clean Air Act as it applies to the heavier light-duty trucks (those above 6,000 lbs gross vehicle weight). Light-duty truck NOx emissions under this option would be controlled to the point where their overall level in 1995 would actually be somewhat below that in 1980, by an estimated 5 percent.

Gasoline-fueled light-duty trucks would meet a 1.2 g/mi standard principally through the application of three-way catalyst systems, although a few of the smallest engines may choose increased EGR rates or retarded ignition timing rather than the expense of a three-way catalyst. Compliance would be relatively straightforward, with about 40 percent of the fleet already equipped with three-way systems. Diesel powered light-duty trucks would be expected to use some combination of EGR and injection timing retard to lower NOx emissions. The only area of difficulty which arises in meeting this option concerns the largest light-duty diesel trucks, such as the General Motors 6.2-liter engine. It is possible that this engine would experience performance and fuel economy penalties in meeting a 1.2 g/mi NOx standard along with the 1987 light-duty diesel particulate standard. Application of an electronic fuel injection timing system may reduce these penalties to some degree, i.e., limit the fuel economy penalty to no more than one percent.

Option 2A establishes a standard of 1.2 g/mi for light-duty trucks up to 6,000 lbs gross vehicle weight or 3,999 lbs equivalent test weight, and a standard of 1.7 g/mi above both of those points. One impact of a tighter NOx standard for diesel light-duty trucks is an increase in engine-out particulate levels. This, in turn, means that compliance with the 0.26 g/mi particulate standard will be more difficult and require a greater reliance on trap oxidizers. Because both the highest NOx emissions and highest particulate emissions are associated with the heavier light-duty trucks, the potential savings associated with maintaining a somewhat less stringent NOx standard for those vehicles has been evaluated. This option also eases the difficulty noted above which the largest diesel light-duty truck engines might have with meeting a 1.2 g/mi NOx standard.

The cutpoint chosen for subdividing the light-duty truck class is 6,000 lbs gross vehicle weight, or 4,000 lbs equivalent test weight. These values define two fairly distinct categories of light-duty trucks, and are parameters in fairly common use. The 6,000 lbs gross vehicle weight criteria is the same as that used in the Clean Air Act to separate heavy-duty engines from light-duty trucks, while the equivalent test weight distinction is used in California standards for light-duty trucks. Use of a test weight distinction in addition to gross vehicle weight is intended to discourage artificial "migration" of vehicles from the lighter group to the heavier group, with its attendant, less stringent standard.

In a fashion analogous to that which led to definition of 1.2 g/mi for light-duty trucks as corresponding to 1.0 g/mi for light-duty vehicles, 1.7 g/mi can be identified as corresponding to a 1.5 g/mi light-duty vehicle standard. Use of a 1.7 g/mi standard for the heavier light-duty diesel trucks will have the same effect as the current 1.5 g/mi light-duty vehicle NOx waiver has for diesel passenger cars. The percentage of light-duty diesel trucks requiring traps to meet the 0.26 g/mi particulate standard will drop, from about 50 to 60 percent to about 20 to 30 percent, while the urban particulate cost effectiveness will improve by a factor of two to three. In exchange for this, 1995 light-duty truck NOx emissions will increase slightly (about 6 percent), but still will not exceed 1980 levels.

Option 2B is similar to Option 2A, except that the relaxed 1.7 g/mi standard would be applied only to heavier diesel light-duty trucks. The principal reason for the split in standards of Option 2A was that of impacts on particulate for diesel engines. Thus an option based only on a relaxed light-duty truck diesel standard deserves consideration. It can be seen from Table 7-3 that this option is distinguishable from Option 2A in terms of gasoline-fueled light-duty truck cost and cost effectiveness, and overall emissions rates.

Option 2C is similar to Option 2B, except that the 2.3 g/mi standard would be retained for the heavier light-duty diesel trucks. Effectively this means that the existing standard would be retained for approximately 60 percent of light-duty diesel truck sales.

Option 3 should be considered as a possible modification to any of the other light-duty truck options through the inclusion of averaging for NOx emissions. At this time, significant benefits attributable to the adoption of such a program have not been identified. On the other hand, there is some potential in this option for slight increases in in-use emissions, as there is in any mobile source averaging program.

Overall, EPA believes that Option 2A is superior to the other options. While Option 1 can not be completely dismissed, Option 2A is preferable because it provides greater environmental benefits and avoids the potential of being inconsistent with the statutory requirement for heavier light-duty trucks. Option 2A is superior to Option 2 because it resolves a potential compliance problem for the heaviest diesel light-duty trucks, substantially reduces the number of traps needed to meet the light-duty diesel particulate standard, and involves only a small penalty in NOx emissions. While the principal motivation for this option concerns diesel light-duty trucks, defining the option as applicable to both gasoline-fueled and diesel light-duty trucks is desirable. The overall impact of a 1.7 g/mi standard for all light-duty trucks above 6,000 lbs gross vehicle weight and lbs equivalent test weight on NOx emissions is small. It has the benefits of regulatory simplicity and equity of standards between the two engine types.

Table 7-4

Impact of Alternative Light-Duty Truck Standards on NO_2 Attainment and Total NO_x Emissions

Total Projected SMSAs Exceeding NO_2 NAAQS
(Expected and High Growth Rates)[1]

LDT Standards	1990		1995		2000	
	Exp	High	Exp	High	Exp	High
1.2/1.7	0	2	0	3	3	6
2.3	1	2	0[2]	5	5	6

Total NOx Emissions in 11 Urban Areas -- All Sources
(Thousands of Tons)

LDT Standards	1990		1995		2000	
	Exp	High	Exp	High	Exp	High
1.2/1.7	1059	1152	1058	1201	1182	1411
2.3	1066	1159	1076	1222	1210	1444
(% Increase)	(.66)	(.61)	(1.7)	(1.8)	(2.4)	(2.3)

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1. Revised analysis based on 1981 design value and Mobile 3 mobile source projections.

2. Under the expected growth and a 2.3 standard, there would be one projected nonattainment area in 1996 increasing to five in the year 2000.

References

1. "Diesel Particulate Study," U.S. EPA, OAR, OMS, ECTD, SDSB.

Appendix A to Chapter 7

I. Derivation of 1995 Emission Inventories

The emission inventory figures for the control options listed in this chapter were derived using standard EPA emissions models. NOx emissions were calculated using a linear rollback model and emission factors (emission rates) from EPA, MOBILE2 program (modified). Particulate emissions were calculated using a methodology developed for the EPA Diesel Particulate Study (DPS).[1] Inventories for the uncontrolled-case and the controlled-case scenario for the proposed NOx and particulate standards were discussed in Chapters 4 and 5. Inventories for the alternative control scenarios discussed in this chapter were calculated using the same models or were derived from the various control scenarios as described below. The derivation of the inventory for each option is given below, organized by vehicle class.

A. Particulate Control for HDDEs (Table 7-1)

Option 1 (uncontrolled case), Option 2 (0.60 g/BHP-hr 1987 and later), Option 4 (0.60 g/BHP-hr 1987-89; 0.25 g/BHP-hr 1990 and later) and Option 4A (Option 4 with the addition of averaging) are all discussed in Chapter 5. They are based on the model employed in the DPS. These outputs, dated November 9, 1983, have been placed in the docket for this action. Option 3 (0.60 g/BHP-hr 1987-89; 0.40 g/BHP-hr 1990 and later) and Option 5 (0.60 g/BHP-hr 1987-89; 0.10 g/BHP-hr 1990 and later) inventories were not discussed in Chapter 5, but are alternative scenarios included in the computer model outputs dated November 9, 1983. The inventories for Option 4B (same as Option 4A, except that line-haul HDDEs, i.e., equivalent to the upper half of class VIII, would meet a standard of 0.60 g/BHP-hr for 1990 and later model years) and Option 4C (same as 4B except line-haul HDDEs would meet a standard of 0.40 g/BHP-hr for 1990 and later model years) were derived from the output of the computer run by combining the HHDDE (line-haul) inventory fraction from options 2 and 3, respectively, with the LHDDE/MHDDE inventory fractions from Option 4A. The emission factors data and methodology for inventory calculation may be found in the DPS.

B. NOx Control for HDDEs (Table 7-2)

Option 1 (no new standards), Option 3 (6.0 g/BHP-hr 1987-89; 4.0 g/BHP-hr 1990 and later) and Option 3A (Option 3 with averaging) inventories are discussed in Chapter 4 (also see Figures 4-1 through 4-8). Together with Option 2 (6.0 g/BHP-hr for 1987 and later model years) these inventories were calculated using the EPA rollback model (November 8, 1983). The outputs may be found in the public docket.

C. NOx Control For LDTs (Table 7-3)

Option 1 (no new standards) and Option 2A (1.2 g/mi for LDTs, and 1.7 g/mi for LDT_2s)* inventories are discussed in Chapter 4 and were based on November 8, 1983 outputs from the rollback model. Inventories for Option 2 (1.2 g/mi for all LDTs) were calculated from outputs of the rollback model performed on October 8, 1983. Option 2B (1.2 g/mi for LDT_1s and $LDGT_2$s, 1.7 g/mi for $LDDT_2$s)* inventories were calculated in rollback model outputs dated November 7, 1983. Option 2C (1.2 g/mi for LDT_1s and $LDGT_2$s, 2.3 g/mi for $LDDT_2$s)* inventories were calculated in rollback model outputs dated May 21, 1984. Copies of these outputs may be found in the public docket.

II. Costs of Control Options

The vehicle/engine lifetime cost estimates for the control options which were considered in developing this proposed rule for HDDE particulate, HDE NOx and LDT NOx emission standards were summarized in Tables 7-1 through 7-3. With the exception of the first option (do nothing) for each combination of regulated pollutant and vehicle/engine class shown in the tables, the costs were derived from the cost estimates for the proposed standards as developed in Chapter 3. The procedures used in developing the costs of the options are described below for each combination of regulated pollutant and vehicle/engine class.

A. HDDE Particulate

Option 2 contained only the first part (1987 standard) of the option which is proposed (4A). The cost was, therefore, derived directly from Chapter 3 and is $31.

The cost estimate for Option 3 was developed on the basis that a fuel economy penalty would not occur as a result of a 0.4 g/BHP-hr standard and that the hardware and development costs involved would be between one-third and two-thirds of those estimated for trap-oxidizers, i.e., between $195 and $390.

The cost estimate for Option 4 was based on 100 percent trap-oxidizer usage because averaging was excluded. The effects on fuel economy were projected to be essentially equal to those for the option proposed (4A). The projected cost is, therefore, between $917 and $1,282.

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* LDT_1 = 0-6,000 lbs GVW or 0-3,999 lbs ETW; LDT_2 = 6,001-8,500 lbs GVW and 4,000 or more lbs ETW.

Option 4B differs from the proposed option in that those engines which are employed predominantly in line-haul operations would continue to meet the 1987 standard in 1990 instead meeting the more stringent 0.25 g/BHP-hr standard. The cost for this option is, therefore, estimated as attributable to the effects on fuel economy and the cost of trap-oxidizers for LHDDEs and MHDDEs. The estimated cost is between $288 and $376.

In Option 4C, line-haul engines would be required to meet the same standard as in Option 3 while other HDDEs would be required to meet the same standards as in Options 4A and 4B. The cost for this option would, therefore, be estimated as the same as that for Option 4B plus the hardware and development costs for HHDDE as were developed in Option 3. The estimated cost is, therefore, between $387 and $573.

In Option 5, the costs for the trap-oxidizers and the fuel economy penalty were assumed to be between 15 percent and 20 percent higher than those estimated for Option 4. The resulting cost estimate is, therefore, between $1,051 and $1,535.

B. HDE NOx

The cost for Option 2 was derived directly from the estimate for the proposed standard. It would consist only of the cost of complying with the 6.0 g/BHP-hr standard which was estimated in Chapter 3 to be $2 for HDGEs and $16-746 for HDDEs.

Option 3 is the approach which is proposed. The costs are, therefore, those which were developed in Chapter 3 for the 1990 standards, i.e., $18 for HDGEs and between $297 and $1,027 for HDDEs.

Specific values for the cost of Option 3A were not developed because specific tradeoffs which could be used in an averaging program could not be identified.

C. LDT NOx

In Option 2, all LDTs would be required to comply with a 1.2 g/mi standard. In the case of LDDTs which are above an emission test weight of 3,999 lbs and a gross vehicle weight of 6,000 lbs ($LDDT_2$) it is expected that additional injection timing retard would have to be employed for compliance with the 1.2 g/mi standard. As a result of the timing retard, it is anticipated that fuel economy could be degraded by between one percent and two percent. The use of electronic injection timing control could limit the fuel economy penalty to no more than one percent and its cost is included. In estimating the cost of this option it was assumed that essentially 100 percent of the large diesel engines used in LDDTs will continue to be used in $LDDT_2$ as was the case in the 1983 model year. With 60 percent of LDDTs using large diesel engines, Option 2 would result in a LDDT fleet fuel economy penalty of between $25 and $50 per LDDT using the fuel economy cost estimate as developed in Chapter 3. The cost of Option 2 for LDDTs is, therefore, between $50 and $78. In the case of gasoline fueled LDTs, it was assumed that Option 2 would necessitate the use of closed-loop three-way-plus-oxidation catalysts on all 8-cylinder gasoline engines used in LDGTs, i.e., 8-cylinder gasoline engines would be used totally in $LDGT_2$ and about 20 percent of LDGTs would be $LDGT_2$ (22 percent were $LDGT_2$ in the 1983 model year). Using the costs developed in Chapter 3, the cost of Option 2 for gasoline fueled LDTs was estimated to be between $66 and $109 including up to a one percent fuel economy penalty for $LDGT_2$s.

Option 2A is the proposed approach, and the costs are those of Chapter 3. The range given in Table 7-3 for cost per vehicle depends on the percentage of LDGTs already equipped with three-way catalysts in model year 1986. The higher cost (and cost effectiveness) assume that three-way catalyst use in 1986 is the same as that in 1984. The lower cost (and cost effectiveness) assume that three-way catalyst installation on LDGTs continues to increase between the 1984 and 1986 model years at the same rate at which it increased between the 1982 and 1984 model years.

In Options 2B and 2C, the effect on gasoline fueled LDTs with respect to technology application would be the same as that of Option 2. The cost would, therefore, be the same, i.e., between $66 and $109 per LDGT.

As in the case of Option 3A for the HDE NOx standard, the development of a cost estimate for the effects of averaging (Option 3 for LDT NOx) was not able to be performed.

III. Derivation of Cost Effectiveness

The cost effectiveness for each particulate and NOx option was based on the per-vehicle costs as described above, the per-vehicle emission factor data presented in the DPS report[1] for particulate, and modified versions of the emission factors given in Chapter 4 for NOx. The emission factors used to calculate the lifetime NOx emissions values were modified as follows from those shown in Chapter 4: 1) The effects of misfueling were removed from the calculation, under the assumption that misfueling would be largely eliminated through future reductions in the availability of leaded fuel. 2) LDDTs between 6,001-8,500 lbs GVW currently maintain a considerable "cushion" between the standard and the actual certification levels. When the new, more stringent particulate standard is implemented for the 1987 model year, it is assumed that these trucks will be certified much closer to the actual NOx standard, due to the NOx/particulate tradeoff. Retaining the 2.3 g/mi NOx standard with the 0.26 g/mi particulate standard would therefore result in a net increase in NOx emissions over the current standards. It is assumed that NOx certification levels at 1.2 or 1.7 g/mi standards will be correspondingly close to the standards. 3) The emission factors were corrected to more accurately reflect the transition to three-way catalyst systems which has already occurred for LDTs.

While none of these changes will significantly alter the overall emission projections of Chapter 4, they do have an impact on the LDT cost effectiveness values. Therefore, this information was used to calculate the cost effectiveness for each option using the methodology discussed in Chapter 6. For particulate the cost effectiveness was determined on an annual basis. For NOx, it was determined on a lifetime basis. The different methods were used for each pollutant to be consistent with past mobile source cost-effectiveness analyses.

Appendix B to Chapter 7

Discussion of Alternatives for Heavy-Duty Engines, from the Preamble to the Proposed Rule

D. Alternatives

As will be seen, control of either particulate or NOx to the degree needed to adequately deal with the environmental needs outlined above involves significant technological challenge and has substantial economic implications. Therefore, EPA has considered a wide range of alternatives in arriving at the final form of today's proposal. These alternatives, and EPA's evaluation of each, are reviewed below. Interested readers are referred to the Alternatives chapter of the Regulatory Impact Analysis for details beyond those presented here.

In general, available alternatives deal with combinations of two factors: stringency of standards and leadtime. In terms of stringency, EPA has considered options varying from no new standards up to the limits of foreseeable technology. The practicality of any of those technological options varies, however, depending on the time allowed for implementation. Therefore, varying amounts of leadtime have also been analyzed. Within the spectrum of standards and leadtime, there is in fact a near continuum of possible options. EPA has attempted to focus specific options at points which are reasonably distinctive in one or more of three areas: technology, benefits, or required leadtime.

1. Heavy-duty Diesel Particulate

Identification of Options

Clean Air Act requirements and the environmental situation both argue strongly for the early implementation of standards to control heavy-duty diesel particulate emissions. On the other hand, the technological barriers to major reductions are of the sort which may require considerable time and effort to overcome. Therefore, EPA has examined separate near- and long-term possibilities. The goal of the near-term options is to implement the greatest degree of control feasible without undue adverse impacts as soon as possible, while the longer term standards are oriented toward attaining more substantial and needed emissions reductions. Considering the time required to complete the rulemaking process and technology considerations for manufacturers to respond to an initial standard, EPA has identified 1987 as the earliest year for a standard. Beyond that, 1990 has been identified as allowing time for implementation of more advanced technology. For these two years, the specific options are identified below along with some of the key considerations for each.

Before turning to individual options, it is important to note that, although the particulate and NOx options are considered separately here, they do in fact interact. In developing and analyzing the following options, EPA has fully considered those interactions when assessing feasibility, technology and cost. The process was carried out in a fashion which would insure the compatibility of the final selected options. For example, the assessment of the number of traps needed to meet the 1990 trap-based particulate options was done on the basis of the existence of the more stringent NOx standard also expected for that year. The two pollutants are discussed separately for clarity of presentation, but readers should bear in mind that they are interrelated and are in the end to be viewed as pairs of particulate and NOx standards.

For 1987:

No standard. This option represents the situation if EPA were to take no action to control heavy-duty diesel particulate emissions. In light of both the Clean Air Act mandate and the significant growth in particulate emissions which will occur without particulate control, this is not a viable option.

0.60 g/BHP-hr. This option represents what EPA believes to be the lowest feasible level in the near term. Current engine emissions are in the 0.4 to 0.8 g/BHP-hr range. The target low mileage emission level associated with a 0.60 g/BHP-hr standard is about 0.46 g/BHP-hr. Thus, some engines already meet the required target, while reductions would be required of others. EPA believes such reductions are feasible with technology and engine calibration changes available in the short term. Such things as improvements in fuel injection systems, increased use of turbocharging, and improvements in engine efficiencies should be able to provide the reductions needed.

For 1990:

Since the 1990 options represent fairly stringent standards, the incorporation of an emissions averaging program in 1990 has been included for all but the "no further control" case. As noted earlier, averaging reduces the risk of non-compliance as well as the cost of stringent standards. It will find its greatest usefulness with the trap-based options.

No control beyond 0.60 g/BHP-hr. While 0.60 g/BHP-hr is a feasible limit for the near term standard, it produces relatively small per-vehicle reductions in particulate emissions. Overall, fleetwide heavy-duty diesel engine particulate emissions would increase by 65 percent between 1983 and 1995 under this option. In addition, such a standard for 1990 or later fails to take advantage of the technological progress that should be made in the three years after 1987. Therefore, 0.60 g/BHP-hr in 1987 without follow-on reductions could not be considered an adequate alternative for longer-term particulate control.

0.40 g/BHP-hr. In moving beyond the 0.60 g/BHP-hr level, EPA believes that a reduction to at least 0.40 g/BHP-hr will be essential to produce further meaningful progress in reducing diesel particulate emissions. This level represents both a sizeable reduction from the 0.60 g/BHP-hr level and EPA's determination of the approximate technological limit for reductions which could be reached without the application of particulate trap technology to heavy-duty diesel engines. It involves substantial improvement over present engines. Some of this improvement will come from techniques already being developed for improved performance and fuel economy (the full cost therefore not being attributable to new standards). However, this level also presumes the further development and application of advanced and costly technology, to a degree which can not be precisely quantified at this time. Future controls will include such things as the anticipated application of electronic controls to engine operations like fuel injection and exhaust gas recirculation, the development of low heat rejection techniques and ceramic materials, increased fuel injection pressures, and other efficiency improving engine changes. Because of uncertainty regarding the mix of control technology which will eventually be used to meet the standard, costs are likewise uncertain. EPA's best judgment estimates are that the discounted lifetime costs for a 0.40 g/BHP-hr standard would be from $195 to $390 per vehicle, depending on fuel economy impact. Particulate emissions in 1995 would be reduced by 35 percent compared to the no-control case, but net heavy-duty diesel particulate emissions would still increase more than 20 percent from 1983 to 1995.

0.25 g/BHP-hr. Reducing particulate emissions to below 0.40 g/BHP-hr is expected to require the application of traps. Use of this technology is still in the early stages of development for heavy-duty diesels, and admittedly much more work is needed before traps will be feasible for production engines. Traps on heavy-duty diesel engines must perform successfully in an environment which is in some ways more challenging than that for light-duty diesel traps (for example, successful regeneration must be possible over a wider range of sustained operating temperatures), and must do so for a generally much longer useful life period. However, at this time EPA sees no insurmountable obstacles to successful application, especially given the substantial amount of leadtime remaining before such a standard would go into effect.

and the already advanced stage of particulate trap development for light-duty diesels.

EPA believes that it will not be possible to move below the 0.40 g/BHP-hr option without the introduction of trap technology. As the standard is lowered below that level, there would be an increasing use of traps within the fleet, with manufacturers making use of averaging to minimize the total number of traps required. Because EPA foresees that some applications will be technically more difficult than others, there is some advantage in a standard which does not require traps on all engines, so that the more technically difficult applications can be avoided. With averaging and a 0.25 g/BHP-hr standard, traps will be needed on an estimated 70 percent of the fleet. At this level, heavy-duty diesel engine emissions would be controlled to the point where emissions in 1995 would be at or even slightly below those of 1983. These emissions represent about a 50 percent reduction from uncontrolled levels, at a per-vehicle cost of about $760 to $1,100, again depending on fuel economy impact.

Urban-oriented variations on 0.25 g/BHP-hr. There is wide variation between different heavy-duty diesel engine applications in the amount of total mileage accumulated within urban areas. Lighter heavy-duty diesels and such vehicles as transit buses, trash compactors, and cement mixers spend the predominant amount of their time in urban operation. Premium heavy-duty diesels used in over-the- road line-haul travel, on the other hand, accumulate most of their mileage in rural inter-city operation. Since EPA's main concern with diesel particulate emissions is their impact on urban air quality, two urban-oriented variations on the 0.25 g/BHP-hr trap option have been evaluated which attempt to focus control primarily on urban vehicles. Both of these variations maintain a non-trap standard for line-haul engines. (Line-haul engines in this case would be defined as those engines used in Class VIII trucks having gross vehicle weight ratings above 60,000 lbs.) Elimination of the need for traps on these vehicles would avoid the most difficult applications, in trade for a moderate loss in overall urban emission reduction. On the other hand, it is also true that line-haul vehicles would be best able to absorb the high cost of traps because of their already high initial cost compared to other heavy-duty diesel engine applications.

The line-haul standards considered are 0.60 and 0.40 g/BHP-hr. The 0.60 g/BHP-hr level is, of course, a much easier standard to meet than the 0.40 g/BHP-hr level. Unfortunately, even the small fraction of line-haul mileage which is urban in nature is sufficient to raise overall heavy-duty diesel particulate emissions in urban areas under this option to above those under a uniform 0.40 g/BHP-hr non-trap standard. Moreover, 0.60 g/BHP-hr could not be considered a technology-forcing standard for line-haul engines in the 1990 timeframe. Thus, a 0.40 g/BHP-hr line-haul standard is the most logical choice to combine with the 0.25 g/BHP-hr trap-based standard. With this combination, there would be a loss of control of about 12 percent in urban areas as compared to the uniform 0.25 g/BHP-hr standard, and 1995 urban heavy-duty diesel engine emissions would be about 7 percent greater than 1983 levels. As can be seen from these figures, even predominantly over-the-road line-haul operation has a significant urban impact.

One difficulty which EPA has had with this approach has been that of developing a regulatory procedure for successfully separating urban from non-urban applications. Heavy-duty diesel engines are currently certified independently from vehicles, and a given engine may be used for a wide variety of applications. An urban designation would require identification of intended vehicle application, and since some engines would be used for both urban and non-urban applications, the manufacturer would be required to develop both trap and non-trap versions of the same engine to be able to take advantage of the optional standard. Such a situation might offer little advantage to the manufacturer. Additionally, an urban option might introduce unwanted competitive effects, for example by favoring manufacturers who made only those engines falling into the line-haul exclusion and who would not have to undertake the resource investments required of other manufacturers to develop trap systems.

0.10 g/BHP-hr. It was noted under the discussion of the previous option that a 0.25 g/BHP-hr standard can be met with traps on about 70 percent of the fleet if averaging is allowed. If the standard were further reduced until essentially 100 percent trap usage were required, the resulting level would be approximately 0.10 g/BHP-hr. This level thus represents the maximum degree of reduction of heavy-duty diesel particulate emissions that can be achieved with the use of trap technology.

Requiring traps on all engine families, however, would increase both the cost and the risk associated with the standard. The technical challenge of successfully applying traps to all engines is much greater than that of applying them to most engines, since in the latter case the manufacturers will be in a position to focus resources on predominant uses and avoid especially difficult cases. At the same time, a 0.10 g/BHP-hr standard would maximize the available emissions reduction, bringing about a 65 percent reduction from uncontrolled levels and reducing total 1995 heavy-duty diesel particulate emissions to a level 33 percent below those in 1983.

There is a modified application for the 0.10 g/BHP-hr option which relates to the control of urban bus emissions. As has been noted earlier in the discussion of averaging, EPA believes it is very important to obtain the maximum degree of control for urban buses. Therefore, in addition to excluding such engines from the averaging program, EPA is considering the establishment of a standard of 0.10 g/BHP-hr for bus engines to insure the fullest use of the emission reduction potential of traps.

Evaluation of Particulate Options

In its evaluation of all of the above options, EPA has considered a number of factors. These included the statutory requirements, anticipated costs and emission reductions, cost effectiveness, and technological requirements for compliance. Some of these factors have already been touched upon in discussion of the individual options. The following material provides further key information for comparing the impacts of the options.

The emissions impacts of the various options are shown in Figure 3, where the options are arranged in order of decreasing emissions. For comparison purposes, the level of 1983 emissions is also shown.

As can be seen, meaningful reductions from uncontrolled levels require a standard of 0.40 g/BHP-hr or lower. Even at that level, heavy-duty diesel particulate emissions in 1995 will be 23 percent higher than in 1983. To further regulate emissions so they do not increase above 1983 levels requires some form of a trap-based standard. Essentially meeting that goal are either the 0.25 or 0.10 g/BHP-hr standards, or the 0.25 g/BHP-hr standard with a 0.40 g/BHP-hr line-haul option. However, it is noteworthy that the 0.60 g/BHP-hr line-haul option does not perform especially well, having emissions actually somewhat higher than the across-the-board 0.40 g/BHP-hr standard. The 0.10 g/BHP-hr standard attains the maximum overall reduction, being 65 percent below the uncontrolled level and 33 percent below 1983 levels.

Figures 4a and 4b present other information related to the economic impacts of the options, in particular, cost effectiveness, which measures the economic efficiency of each option, and midpoint cost per engine (including operating costs). For clarity of presentation, the cost per engine values plotted are the midpoints of the ranges (based on possible fuel economy impacts) of estimated costs.

Figure 3

1995 Urban Heavy- Duty Diesel
Particulate Emissions

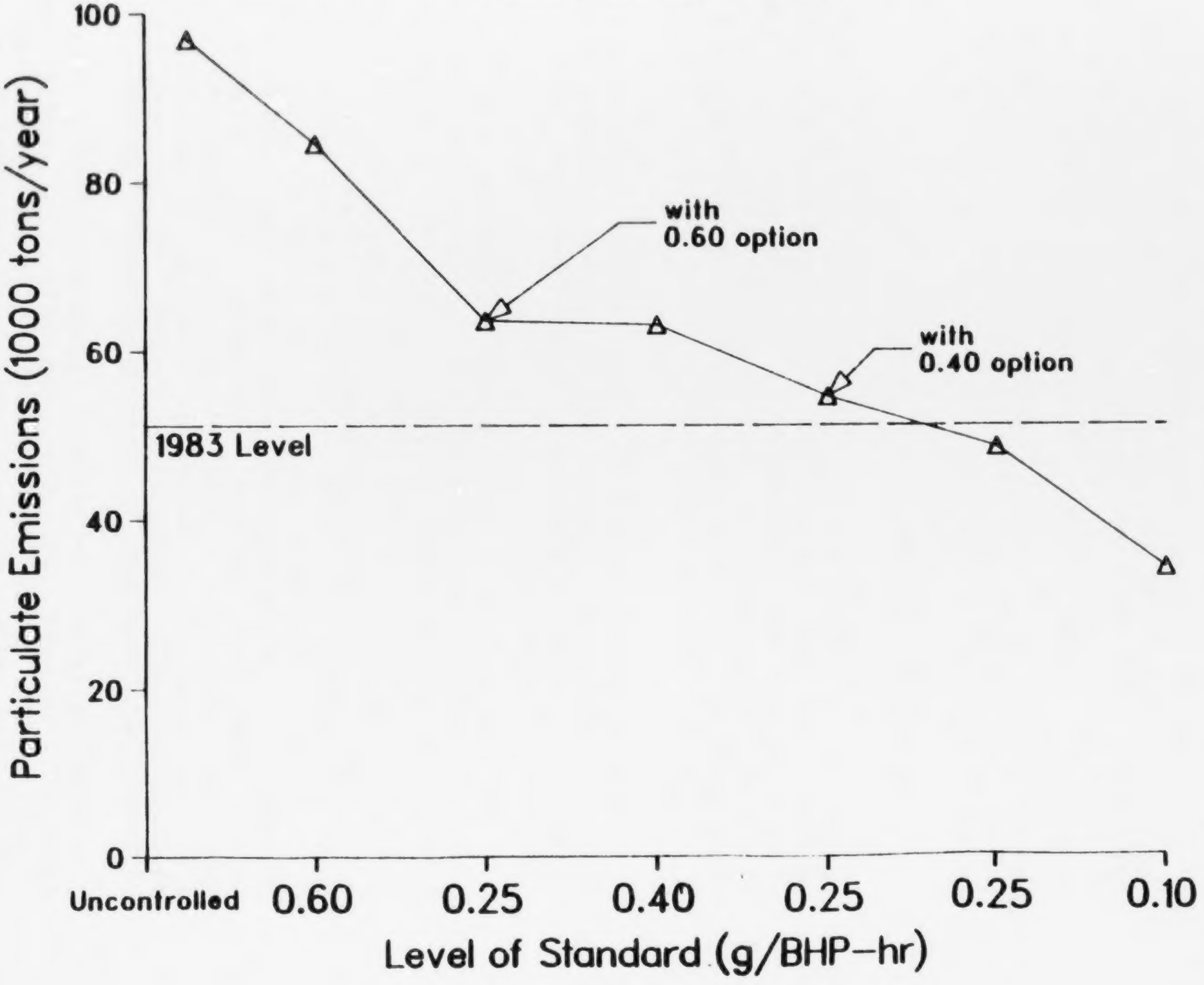


Figure 4a

Midpoint Cost Effectiveness of Heavy-Duty Diesel Engine Particulate Control

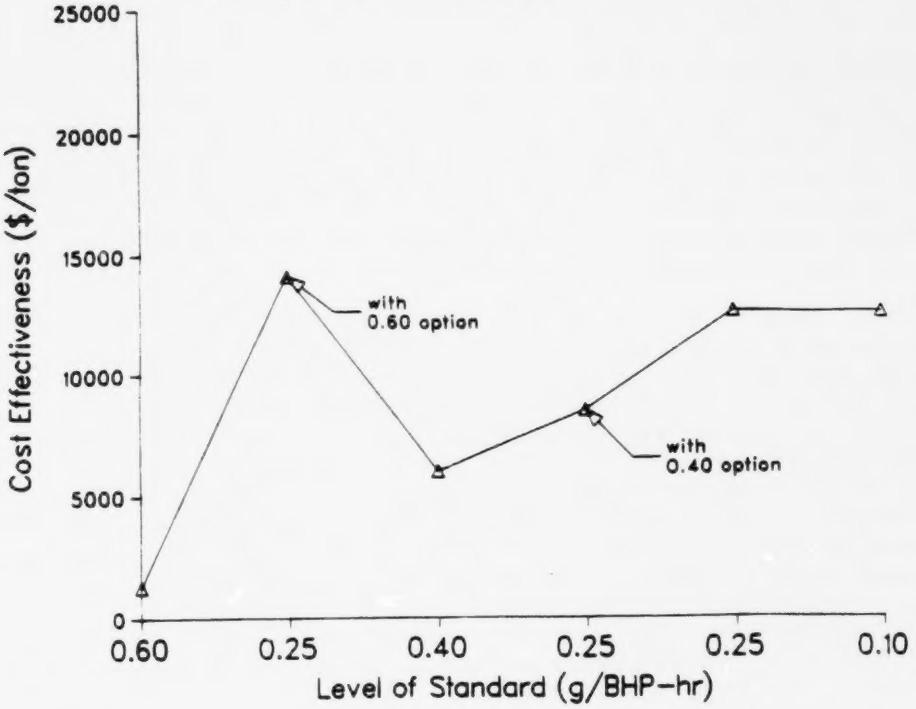
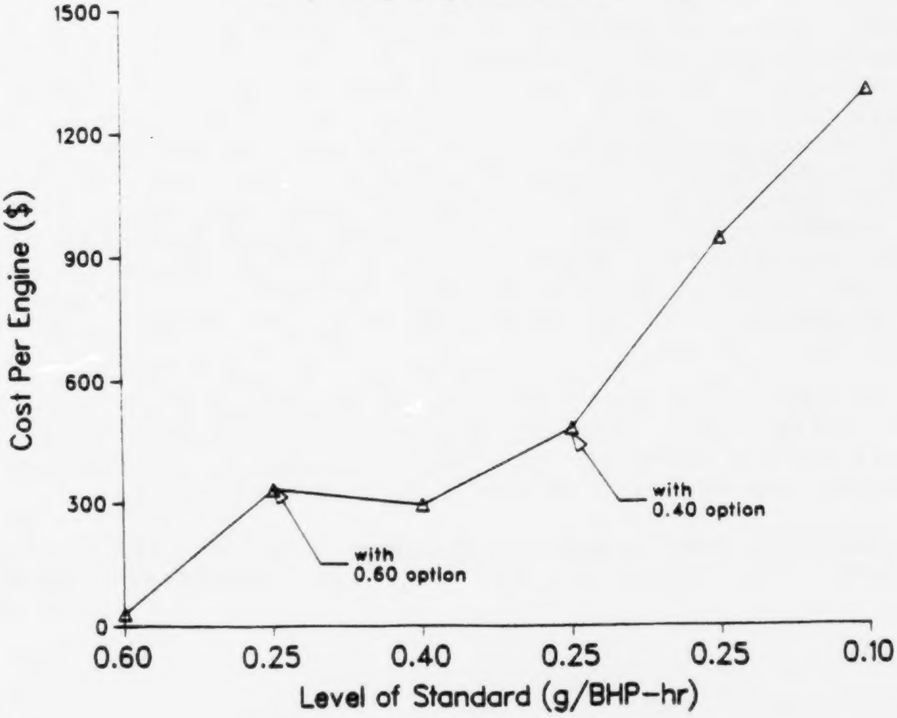


Figure 4b

Midpoint Cost Per Engine of Heavy-Duty Engine Particulate Control



Cost effectiveness values commonly increase (worsen) as the standards get lower. However, there are two exceptions to this trend in Figure 4a. These are the 0.25 g/BHP-hr standard combined with the 0.60 g/BHP-hr standard for line-haul trucks, which is the least cost effective of the options shown, and the 0.10 g/BHP-hr full-trap standard, where the cost effectiveness is shown as equal to that of the 0.25 g/BHP-hr standard.

The standard of 0.25 g/BHP-hr combined with 0.60 g/BHP-hr for line-haul trucks is the least cost effective of the options presented in Figure 4a. As was shown in Figure 3, urban heavy-duty diesel particulate emissions are actually slightly greater under this option than under an across-the-board standard of 0.40 g/BHP-hr. At the same time, 0.40 g/BHP-hr represents a non-trap option, while 0.25 g/BHP-hr with 0.60 g/BHP-hr for line-haul trucks would require about 70 percent of urban heavy-duty diesels to be equipped with traps. This results in substantially higher costs, relative to the 0.40 g/BHP-hr standard, while the total emissions reductions are slightly less. The resulting cost effectiveness value of about $15,000 per ton of urban particulate emission reduction makes this an unattractive option.

Turning to the 0.10 g/BHP-hr standard, EPA believes that the cost effectiveness of this standard will actually be somewhat worse than that of the 0.25 g/BHP-hr standard, but is not at this time able to quantify the difference. The maximum benefit and least cost applications will have already been used to meet the 0.25 g/BHP-hr standard (with averaging), so that subsequent use of traps on additional engines might be somewhat less cost effective. Among the factors arguing for higher cost at the 0.10 g/BHP-hr level are greater development costs, the need to design to lower low-mileage-target emission levels, the use of higher quality components, the probable need for more frequent trap regeneration, and the increased risks associated with in-use compliance. Accordingly, although emissions would be lower under a 0.10 g/BHP-hr standard, it appears that this standard would be less cost effective than is shown in Figure 4a.

On the other hand, Figure 4b indicates that even when these extra cost factors are not considered, these two options differ markedly in cost per engine, reflecting the increased use of traps at the 0.10 g/BHP-hr level.

Although not shown in Figures 3 or 4, EPA has also examined the impacts of a 0.25 g/BHP-hr standard implemented without the benefit of an averaging program. Such an approach requires 100 percent trap use, and therefore incurs essentially the same cost as the 0.10 g/BHP-hr standard does, although the use of some less efficient systems would be expected to reduce costs somewhat. The emission reduction benefits, however, remain virtually unchanged. The result is a clearly less efficient regulation, having a cost effectiveness of approximately $16,000 per ton.

Based upon the available information, overall conclusions about some of the options are readily apparent. For 1987, the proposal of a 0.60 g/BHP-hr standard is the clear choice as the only option which generates feasible emission reductions in the near term. For 1990, on the other hand, continuing with 0.60 g/BHP-hr is not acceptable both because it produces insufficient emissions benefit and because it fails to satisfy the requirements of the Act. The beneficial effects of averaging, both on technological difficulty and on overall costs, also support the inclusion of this program for the long-term standards. This is true regardless of the level of the final standards, although there would be more benefit if a trap-based standard were promulgated.

Beyond these decisions, the choices for long-term standards become more difficult. Both the non-trap and trap-based standards will demand significant technological advances. Indeed, it appears that the technological difficulty of a 0.40 g/BHP-hr standard using non-trap techniques is at least as great for some engines as that of a 0.25 g/BHP-hr standard using traps. One of the risks of the 0.40 g/BHP-hr level is that it may in fact turn out to require traps to meet such a standard. Given this situation, EPA believes that a trap-based standard is preferable. Not only would it provide needed emission reductions at reasonable cost, but it would insure continued progress in the development of traps for heavy-duty diesel engines. Trap technology is being successfully applied to light-duty diesel engines and is expected to be available to meet 1987 standards for those vehicles. Failure by EPA to require the development of traps for heavy-duty diesels would not seem reasonable considering the statutory mandate and the significant urban impact of heavy-duty diesel particulate. Traps are unlikely to be applied to heavy-duty diesels unless standards require them. Finally, as has already been noted, even the 0.25 g/BHP-hr trap standard will succeed only in holding heavy-duty diesel emissions at current levels, making no actual reductions beyond that point.

Within the range of trap-based standards, there are four options. These are the 0.25 g/BHP-hr standard, the 0.25 g/BHP-hr standard with a line-haul option of either 0.60 or 0.40 g/BHP-hr, and the 0.10 g/BHP-hr standard. EPA believes that the maximum stringency 0.10 g/BHP-hr standard is inappropriate at the present time. Its requirement for essentially 100 percent trap use greatly increases the risk that some engines might be unable to meet the standard by 1990. The 0.25 g/BHP-hr standard will allow a more orderly development and application of technology because some of the more intractable applications can be avoided. At the same time it meets the requirements of the statute and promises to maintain overall heavy-duty diesel particulate emissions at essentially current levels. As for the line-haul options, the 0.60 g/BHP-hr standard has little to recommend it. It requires no further control beyond 1987 for the affected engines, significantly increases overall fleet emissions, and is the least cost effective of the options considered here. The 0.40 g/BHP-hr line-haul standard, on the other hand, involves a trade of some emission benefit for enhanced overall cost effectiveness. For this reason, EPA currently favors inclusion of the 0.40 g/BHP-hr line-haul option in the Final Rule. However, before such an approach could be finalized, regulatory means of identifying urban and non-urban applications would have to be developed, and the unwanted competitive effects would have to be mitigated. The Agency thus solicits comment on this approach and its possible usefulness, and is specifically interested in suggestions as to how the workability of this concept might be improved.

While EPA does not believe that a standard of 0.10 g/BHP-hr should be proposed for all engines, that standard may be appropriate for urban bus engines. The possibility of implementing a 0.10 g/BHP-hr standard for urban buses was mentioned earlier as a means to insure maximum control of these engines. As a group, these engines have less diversity in both engine characteristics and in operating patterns than do heavy-duty diesels as a whole. EPA believes that, given the use of trap technology, these engines may be able to meet a 0.10 g/BHP-hr standard for little extra cost beyond a 0.25 g/BHP-hr standard, since the trap technology currently envisioned appears to provide the required efficiency to meet the lower standard. At this level the urban cost effectiveness appears very good, primarily because these buses accumulate all of their mileage in urban areas rather than having a portion of emissions benefits discounted as rural. The cost effectiveness of the 0.10 g/BHP-hr standard for urban buses is estimated to be about $3,300 per ton.

Since EPA has not identified significant cost differences between these two standards, the 0.10 g/BHP-hr level appears preferable. At the same time, recognizing that such costs may be identified by public comment on the proposal, the Agency remains open to eventually setting a 0.25 g/BHP-hr standard for urban buses and is proposing both options for comment.

EPA believes strongly that trap technology is feasible and cost effective for most heavy-duty diesels for the 1990 model year, yet it also recognizes the possibility that its judgment could be changed by information developed during the public comment period. Therefore, it is also prudent to indicate what course EPA would choose for non-trap standards in that eventuality. EPA's plan at this time would be to implement the 0.40 g/BHP-hr level should a non-trap standard prove to be necessary.

In summary, EPA believes that some degree of immediate control should be implemented, and that a standard of 0.60 g/BHP-hr is feasible in the 1987 timeframe. Beyond that, substantial further reductions are called for and appear to be feasible for 1990. It is EPA's further judgment that trap technology can be successfully applied to most heavy-duty diesel engines in that timeframe, and that the added emission reductions possible with traps justify the increased costs of a 0.25 g/BHP-hr standard, and perhaps a 0.10 g/BHP-hr standard for urban buses. If the problems associated with implementing a 0.40 g/BHP-hr line-haul standard in conjunction with the 0.25 g/BHP-hr standard can be resolved, EPA also favors including this option in the Final Rule.

2. Heavy-duty Engine NOx

EPA continues to believe, as originally indicated in the NOx advance notice, that the statutory 75 percent reduction standard is not feasible for heavy-duty diesel engines. A NOx standard will have to be developed either as a temporary revision, based on such things as cost and fuel economy impacts, or as a permanent change based upon lack of environmental need. From the earlier discussion of the environmental need for NOx control, there may or may not be a need for controlling future motor vehicle NOx emissions.

In developing NOx control options, EPA has decided to use common standards which are appropriate for both gasoline-fueled and diesel heavy-duty engines. While it would be possible to have separate standards for gasoline-fueled and diesel engines, there would be little environmental benefit from doing so in this case. As was noted in the discussion of environmental need, NOx emissions from heavy-duty gasoline engines are expected to decline in future years even without additional control. Therefore, so long as a reasonable degree of control is established for gasoline engines, they will not pose a significant concern relative to future NOx emissions.

In a manner similar to the heavy-duty diesel particulate options, EPA has examined NOx control options in two timeframes, near-term (1987) standards and longer-term (1990) standards. For NOx there is an added leadtime dimension because of the statutory leadtime provisions of Section 202(a)(3)(B) of the Clean Air Act. The choice of 1987 does not satisfy the four year leadtime provision of that section, but EPA has explicitly considered the amount of available leadtime in developing 1987 options and, as indicated in the earlier discussion of statutory provisions, believes the now conflicting requirements of the Act necessitate such an approach. In addition, manufacturers have been aware since the January 1981 advance notice that EPA planned to require substantial NOx emission reductions. This fact has in essence given them three additional years to begin to prepare for new NOx standards. While this fact does not in any way excuse EPA from the need to allow adequate leadtime for a new standard after its promulgation, it has allowed progress to be made in heavy-duty engine NOx control and reduced the required leadtime for an early standard.

For 1987:

No new standard. Under this option, the 1986 NOx standard would remain unchanged. This approach would have to be implemented under Section 202(a)(3)(E) after the Administrator has studied the impact of motor vehicle NOx emissions on public health and welfare. However, current engines are actually operating below the level of the standard (generally in the 4 to 8 g/BHP-hr range), so that future emission levels could increase even more than projected if manufacturers were to take advantage of potential increases in trade for improved fuel economy or easier compliance with particulate emission standards.

6.0 g/BHP-hr. EPA's evaluation of current emission levels and the potential for near-term reductions from heavy-duty diesel engines indicates that a standard of 6.0 g/BHP-hr is feasible for 1987. This standard represents a modest decrease from current engine emissions (about 15 percent below current levels) which should be attainable in the short term with techniques compatible with the proposed 0.60 g/BHP-hr particulate standard. Techniques expected to be used include improvements to fuel injection systems, injection timing retard, increased use of turbocharging and aftercooling, minor engine modifications and improvements to engine efficiencies.

This option is considerably less stringent than the 4.0 g/BHP-hr level envisioned in the advance notice, in spite of the time which has elapsed since then, and in spite of the fact that manufacturers face a standard for their California models of 5.1 g/BHP-hr NOx on the EPA transient test (or 4.5 g/BHP-hr HC plus NOx on the 13-mode steady state test) for 1984. However, a Federal standard below 6.0 g/BHP-hr would not be feasible for 1987, principally because of leadtime constraints. The 6.0 g/BHP-hr level itself will present a challenging task in that timeframe. Standards would need to be delayed several years (see the discussion of 1990 standards below) to move significantly below that level.

Gasoline-fueled heavy-duty engines will be able to readily meet a 6.0 g/BHP-hr standard in 1987. About one third of current engines are already capable of meeting such a standard, and those remaining have well established techniques at hand for compliance. Recalibrations of air/fuel ratios, enhanced exhaust gas recirculation (which will already be in use on most heavy-duty gasoline engines), and ignition timing retard will be able to satisfy a 6.0 g/BHP-hr standard with no significant impacts on performance or fuel economy.

EPA views the 6.0 g/BHP-hr 1987 option as essentially a stop-gap measure to obtain a feasible level of control in the short term. The Agency's main concern is directed at the longer-term 1990 standard. Although the proposal as structured provides a three-year period for the interim standard, the Agency does not view it as essential to maintain such a period should it, for example, turn out that the 1987 proposed level has to be delayed. In such an event, the Agency might choose to abandon the interim standard or to implement it for a one or two year period, depending on the situation. Any decision to change or delay the 1990 standard will be an independent judgment based only on facts pertinent to the feasibility of that standard for that year. (A decision about 1990 would, of course, consider as relevant such facts as the impact of a delayed interim standard on the availability of manufacturers' resources for meeting a long-term standard.) Commenters on the proposal should treat the near-term and long-term standards as separate and distinct issues, and not assume that a delay in the 1987 standard would mean an automatic delay in the 1990 standard.

For 1990:

No control beyond 6.0 g/BHP-hr. If no additional control is adopted for 1990, then heavy-duty engine NOx emissions will continue to increase much as projected under current standards. A 6.0 g/BHP-hr standard would result in heavy-duty engine NOx emissions in 1990 being over 50 percent greater than in 1980. Such a standard also would fail to meet the statutory requirement for a temporarily revised standard based on technological, cost, or fuel economy considerations. The Administrator would have to issue the standard under Section 202(a)(3)(E) after studying the effects of motor vehicle NOx emissions on the public health and welfare.

4.0 g/BHP-hr. In order to deal successfully with the problem of future growth in NOx emissions, a substantial reduction beyond the 6.0 g/BHP-hr level is necessary. EPA believes that further reductions are available, and that projected improvements in technology argue for lower future standards. Unfortunately, heavy-duty diesel engines, which form the bulk of the problem which must be addressed, are limited in their capability for reductions in NOx. Based upon current knowledge of diesel NOx control technology, EPA believes that a 4.0 g/BHP-hr standard represents the approximate limit of available control without unacceptable impacts on fuel economy, engine durability or engine-out particulate levels. Primary sources of NOx control lie in the areas of electronically programmed exhaust gas recirculation, electronic management of fuel injection, charge air cooling, and engine modifications to improve efficiency and enhance combustion. These will be implemented in concert with changes needed for particulate control. As noted in the discussion of the 0.40 g/BHP-hr particulate option, much of this technology is already targeted for introduction on heavy-duty diesel engines in the late 1980s for reasons apart from emissions control (fuel economy improvements). The full cost, therefore, should not be attributed to emissions control requirements. There is also uncertainty as to the final complement of technologies which will be used to meet a 4.0 g/BHP-hr standard, introducing further variability into actual costs. Discounted lifetime cost would be about $300 to $1,000 per vehicle, depending on fuel economy effect. Total discounted NOx emissions in 1995 would only be about 7 percent greater than 1980 levels under this option.

In establishing the 4.0 g/BHP-hr option, full consideration has been given to the interactions which will occur between NOx and particulate standards for heavy-duty diesel engines. The most difficult combination of standards would pair the 4.0 g/BHP-hr NOx standard with the 0.40 g/BHP-hr non-trap particulate standard. With this combination, great care would have to be exercised in balancing tradeoffs between NOx and particulate emissions to bring engine-out levels of both pollutants below the standards. The difficulty of the 4.0 g/BHP-hr NOx standard would be eased somewhat when paired with the trap-based 0.25 g/BHP-hr particulate standard. The use of traps for particulate control will allow some increase of engine-out particulate in favor of lower NOx levels. In any event, EPA recognizes that the combination of a 4.0 g/BHP-hr NOx standard with either a 0.40 g/BHP-hr or a 0.25 g/BHP-hr particulate standard will represent a very difficult challenge for conventional diesel engine technology.

Heavy-duty gasoline engines will also be able to meet a 4.0 g/BHP-hr option for 1990. Enhanced use of exhaust gas recirculation will be the primary means of compliance, along with engine modifications to improve tolerance for exhaust gas recirculation without adverse fuel economy or performance effects. These modifications might include improvements to combustion chamber efficiency, fast burn combustion techniques, some use of electronic controls, and general engine efficiency improvements. Similar non-catalytic reductions of NOx have been attained for light-duty vehicles, and considering the amount of leadtime remaining before 1990, EPA believes that the necessary improvements will be attainable for gasoline-fueled heavy-duty engines.

The cost-effectiveness of the 4.0 g/BHP-hr option is under $400 per ton for both gasoline-fueled and diesel engines. Cost effectiveness turns out not to have been a significant discriminator for any of the NOx control options, for either heavy-duty engines or light-duty trucks, because it has been relatively low for all of the options considered. Therefore, cost effectiveness will not be discussed further in the context of NOx control options.

In summary, the 4.0 g/BHP-hr standard in 1990 combined with a 6.0 g/BHP-hr standard in 1987 represents what EPA believes to be the proper level of control for heavy-duty engine NOx emissions, given the technological limitations of current diesel engines.

Chapter 8

Benefit-Cost Analysis

I. Introduction

This chapter provides a detailed analysis of the benefits of controlling heavy-duty diesel vehicle (HDDV) particulate emissions and compares these to the societal costs of emissions control. This analysis augments the cost-effectiveness analysis of the previous chapter in two ways. First, while cost-effectiveness analysis is a useful tool for comparing two or more options, it cannot answer the economic question of whether any of the options are worthwhile. In contrast, by virtue of its use of a common unit of account -- the dollar -- benefit-cost analysis permits comparisons of the relative merits of different control levels, or controls on different vehicle classes. Second, Executive Order 12291 [1] requires explicit valuation and comparison of the benefits and costs of major regulatory decisions. Neither of these two reasons is sufficient for benefit-cost analysis to itself determine what standard is best. In the first place, this may not be possible given explicit language on what information is admissible in making a decision and given the technical stringency required in the Clean Air Act. Secondly, other factors not taken into account, or not easily quantifiable, are included in the decision process. Rather, benefit-cost analysis provides a convenient way to organize economic impact information. It cannot legitimately be utilized in isolation from the previous data and analysis in this RIA. It simply provides some perspective on the value of improvements that flow from mobile source control of diesel particles.

Benefit analysis attempts to estimate the willingness of consumers in the aggregate to pay for reductions in pollutants. Since it is grounded on the valuation individual citizens place on environmental improvement, it is philosophically in harmony with basic democratic traditions. To the extent we capture this metric in practice, comparison of benefits and costs can tell us whether it is economically efficient (in the sense that some other allocation of resources would make us in net better off) to impose regulation of a given stringency on diesel particles. Capturing a true willingness-to-pay measure of benefits is, however, a difficult task since well-established markets for environmental amenities seldom exist. Thus, the process of measuring benefits is not usually as straightforward as that for measuring costs.

The analysis is divided into two main sections. The first addresses estimation of the benefits of controlling HDDV particulate emissions; and the second, the estimation of HDDV particulate control costs. The cost data underlying the analysis are derived from other sections of this report, associated EPA reports, and contractor reports. The benefits data and analysis are derived from a report by Mathtech Inc. This analysis is highly detailed, having utilized metropolitan counties as the basic geographic unit.

II. Benefits and Costs of HDV Particulate Controls

Regulatory options for control of mobile source particles are being considered for heavy-duty vehicles. Particulate control for light-duty vehicles has recently been postponed to the 1987 model year at the .2 g/mi level for automobile and .26 g/mi for light-duty trucks. In the first subsection a detailed description of the benefits of two HDDV standards -- at .25 g/BHP hr. and at .10 g/BHP-hr. -- is presented. The second subsection describes the computation of the control costs in a format comparable to the benefits. The last subsection presents a B-C analysis of some of the regulatory options presented elsewhere in this RIA. These include: (1) .6 g/BHP-hr. for 1987 and .4 for 1990; (2) .6 for 1987 and .25 for 1990; (3) .6 for 1987 and .25 with averaging for 1990; (4) .6 for 1987 and .25 with averaging for 1990 except line-haul trucks which remain at .6; (5) .6 for 1987 and .25 with averaging for 1990 except line-haul trucks which are to meet .4; and (6) .6 for 1987 and .10 for 1990.

A. Particulate Benefit Analysis for HDDVs

1. Overview of Benefits Estimation Methodology

Estimation of the benefits of reducing diesel particles is based directly (or by extrapolation) on the geographically disaggregated estimates presented in a recent Mathtech report [2]. The Mathtech analysis covers both health and welfare effects. The health benefits are subdivided into noncancer mortality, chronic and acute noncancer morbidity, and cancer mortality categories. Welfare effects include visibility and household soiling categories. Though diesel odor is potentially an important aesthetic effect, it is not valued in the Mathtech report.* The scope of coverage of effects is broad, but not entirely comprehensive, as will be illustrated in the following two sections. No fundamentally new concentration-response or damage effects research is presented in the Mathtech study. Ideally, benefit estimation would be accomplished using data developed specifically for diesel emissions and associated undesirable effects. This is unfortunately precluded by the absence of scientific data of this sort. Thus, Mathtech's contribution is one of critically reviewing the relevant particulate related studies and developing a range of estimates that best represent prevailing knowledge.

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*The odor problem is relevant to particulate standards, since some particulate control technologies contribute to odor reduction. On-going work to value reduced exposure to diesel odor is expected to be completed in mid 1984.

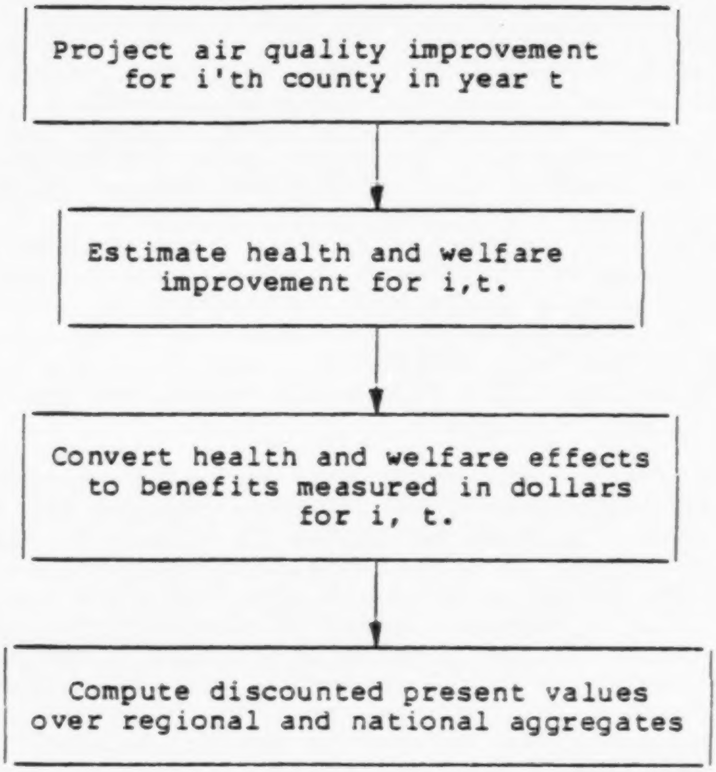
The benefit estimation procedure follows the four steps outlined in Figure 8-1. In the first step, the change in air quality is projected annually over the 1987-2000 period of analysis for each metropolitan county with a population over 100,000 people. This computation measures the improvement achieved after implementation of a selected diesel particulate emissions standard, and specifically accounts for the number of operating diesel vehicles, miles traveled, and emissions factors. The second step involves estimation of the various health and welfare improvements that are predicted given a lower ambient concentration of diesel particles. This step employs the research findings extracted from published studies. These generally take the form of concentration-reponse functions from which county estimates of effects are generated for each year.

The third step imputes a monetary value to the various changes in health and welfare measures. These changes are valued in a variety of ways. Reduced mortality is valued by first determining the reduction in annual mortality associated with lower emissions. The value individuals place on this reduced risk (determined from a separate group of studies) is then used to value the benefit to the population at risk. The flavor of willingness-to-pay to avoid premature mortality risk is intrinsic to this approach. In contrast, reduced instances of morbidity are valued by reduced costs, either in medical expenditures or in work loss days, the latter based on average regional wage rates. The cost to the individual in terms of pain and suffering is omitted, so that a downward bias results from valuing morbidity in this way. Welfare effects are valued, in the case of soiling and materials effects, on the basis of changes in consumer surplus, which is the common practical method of measuring changes in willingness-to-pay; and in the case of visibility, on the basis of willingness-to-pay data gathered from surveys designed to simulate market bidding processes.

The final step shown in Figure 8-1 involves time aggregation (using the OMB 10% discount rate guideline) and spatial aggregation. The period of analysis covers 1987-2000. The heavy-duty particulate standard is assumed to take effect in 1988. The choice of 1987 as the initial year was dictated by a companion Mathtech study of light-duty diesel particles. The final year was selected because it is as about as far into the future as one could practically predict the various growth factors. In any case, after 14 years, the process of discounting reduces both costs and benefits to only

Figure 8-1

Benefits Estimation Procedure


Project air quality improvement for i'th county in year t
Estimate health and welfare improvement for i,t.
Convert health and welfare effects to benefits measured in dollars for i, t.
Compute discounted present values over regional and national aggregates

roughly a third of their original magnitude in the last year. Thus, truncation at this point does not greatly affect the outcome of the benefit-cost comparisons.

An extrapolation procedure was required to develop national benefit estimates. The basic analysis covers only 41 metropolitan counties (roughly 25% of total metropolitan population). These are the counties which have population exposure monitors (in NAMS network) that measure CO concentrations. CO concentration is used in a proportional formula to ascertain particulate concentration. The national estimate of benefits (covering all SMSAs with a population greater than 100,000 people) is derived via an estimated relationship between particulate emissions and vehicle miles traveled, which is necessary for counties where the monitored CO proxy for particulates is unavailable.

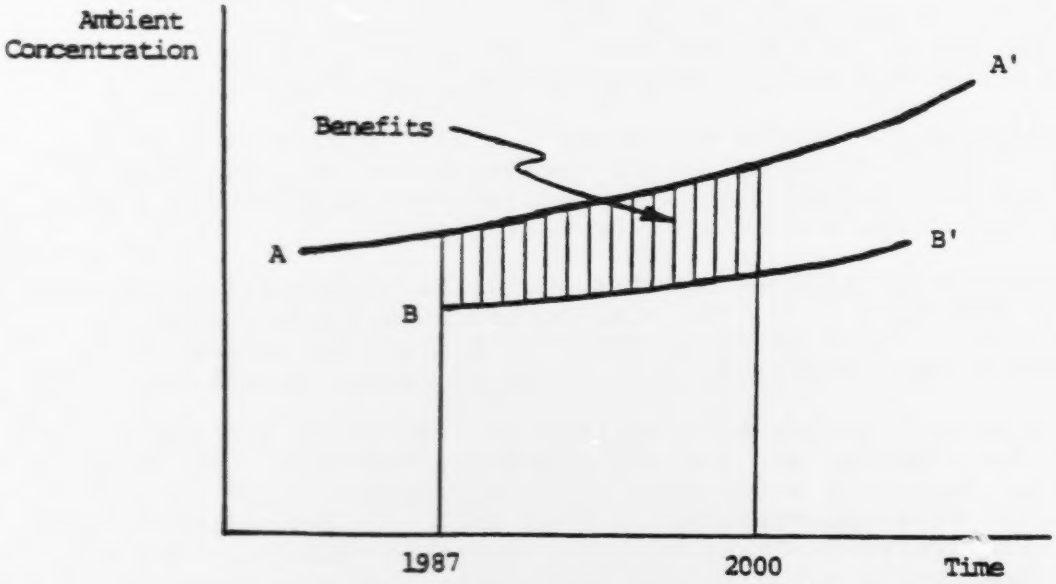
Steps two and three will be discussed in greater detail in the following two sections that focus on health and welfare effects respectively. The remainder of this section concentrates on the air quality modeling and aggregation procedures contained in steps one and four.

Figure 8-2 illustrates graphically the connection between air quality and the measure of benefits over time. The curve AA' in Figure 8-2 depicts the uncontrolled (baseline) diesel particulate emissions, which increase over time given expected increases in diesel vehicle sales. The curve BB' represents the reduction in diesel emissions associated with a selected diesel particulate standard. Benefits are computed annually on the basis of the difference in concentrations between these two curves. Projecting diesel particle loadings is not straightforward, however, since no ambient monitoring network exists for fine particulate concentrations.

Mathtech utilizes an approach similar to that in the National Research Council study [3]. That approach takes advantage of similar relationships between CO emissions and CO ambient concentrations and DP emissions and DP ambient concentrations. The comparability between emissions and ambient concentrations for CO and DP is due to the fact both are predominately mobile source emissions with similar dispersion patterns. Assuming proportionality, ambient DP concentrations can then be projected from CO and DP emissions factors and monitored CO ambient concentrations. The emissions factors (and changes in emissions factors) account for the number and age of vehicle by type, deterioration in emissions rate with age, and VMT by vehicle type and age. Projections of new vehicle sales and a scrappage model are thus an integral part of the air quality component of the benefit model.

Figure 8-2

Time Stream of Benefits and Air Quality Change



In the baseline case, some controls have already been engineered into existing vehicles. By 1986 cars are projected to be emitting at about .32 g/mi (assuming they meet a NO_x standard of 1.0 g/mi and the 5.7 liter GM engine line is dropped from production); light-duty trucks at .56 g/mi (assuming NO_x standard of 1.2 g/mi); and all heavy-duty trucks at .7 g/BHP-hr., until 1988 when the latter is assumed to fall to .6 g/BHP-hr.

Given a projected air quality change in a county, incremental benefits can be computed for control options for any study whose results are presented in concentration-reponse form. Choosing the set of studies that best represents real benefits is a difficult task. The potential for undercounting or double counting in the process of aggregation is substantial. Further, studies of similar effects areas may differ in terms of credibility and accuracy of results as well as the breadth of coverage. Partly for these reasons, and partly due to institutional constraints, Mathtech presented four aggregation alternatives.

Alternative A is designed to be consistent with the Clean Air Scientific Advisory Committee [CASAC] review of the health literature [4]. This review was very conservative in distinguishing between highly reliable and less reliable quantitative evidence. Welfare effects are excluded, since CASAC has not determined that studies of welfare effects provide highly reliable quantitative evidence. The incomplete coverage of both health and welfare benefits under Alternative A implies this aggregation scheme almost certainly substantially underestimates true benefits.

Alternative B adds, conservatively, studies CASAC judged less reliable but still with scientific merit. These provide the only available evidence of the potential magnitude of benefits in some categories (e.g., noncancer mortality). Alternative B includes minimum estimates of soiling, but assumes visibility benefits are zero. The predominant conservative bias probably means that Procedure B also underestimates true benefits.

Alternative C includes estimates for all categories with the exception of soiling and materials damage in the manufacturing sector which is considered highly speculative. Alternative C provides the best point estimate of true benefits.

Alternative D utilizes studies that give higher estimates than C, filling some gaps in C, but also probably double-counting in some instances. While benefits could be as high as indicated by Alternative D, the prevailing bias is in an upward direction.

The four aggregation alternatives provide quite disparate results. For example, for the .25 g/BHP-hr. standard, the benefits estimated by Procedure A are $209 million (present value in 1987 for 1987-2000 interval measured in 1983 dollars); Procedure B, $752 million; Alternative C, $6638 million; and Alternative D, $12,017 million. One should not conclude from these that the range of uncertainty is almost two orders of magnitude, since the range is a function of study selection. Rather, the reader should conclude that selecting the most credible study set is important. It is encouraging that the estimate generated by Alternative C is reinforced by ancillary evidence. Property value and wage-based studies, that directly relate ambient particulate concentrations to dollar value (effectively by-passing the usual damage function chain), are consistent with the aggregated health and welfare estimates from Alternative C. Cross-checking the individual health and welfare benefit estimates is not possible, however, since the property and wage studies cannot be disaggregated. The principle underlying property and wage studies is rather simple. Differences in air quality are expected to be capitalized into property values, and may show up in wage differences geographically as well. One would expect, however, that these methods underestimate actual benefits, since people will not adjust for environmental effects they do not know about. Many of the health effects of particles are not common knowledge. Since we would expect Alternative C to be higher by some portion of the health component, the relationship between Alternative C and the property value and wage studies shown in Table 8-1 tends to reinforce the credibility of Alternative C. The point estimates in the remainder of this chapter are based on Alternative C.

2. Estimation of Health Benefits

Though at times controversial, placing an economic value on reducing the risks of morbidity and mortality provides a way to lend some perspective to the many different health impacts attributed to air pollution. For example, the major emphasis on health risks associated with diesel particulate emissions has been on cancer [5]. Yet, because the cancer risk is less proximate in time (given a fairly long latency period) relative to noncancer health effects, and because effects do not pose that large a risk unless exposures are over a lifetime, noncancer risks turn out to be far more important in monetary terms.

As alluded to earlier, valuing changes in mortality is accomplished by computing the change in the probability of environmental health symptoms, which is then monetized using separate wage premium and other data that indicate willingness-to-pay to avoid increased occupational or other kinds of risk. To noneconomists, the attempt to quantify the value of life often seems presumptuous. Indeed, for most people no finite payment would be acceptable in exchange for loss of life. But an individual is generally not confronted with certain death as a result of pollution. Rather, he may face the possibility that there is one chance in a million, for example, that an environmentally induced cancer will occur. What must be valued, then, isn't the metaphysical question of the value of a particular

Table 8-1

Benefit Estimate Comparisons Among Valuation Techniques
(present value in 1987 in millions of 1983 dollars
for 1987-2000 period)

Estimate	Alternative C	Property Studies	Wage Studies
min.	1243.	1730.	2877.
point	6635.	3461.	5812.
max.	21,105.	5768.	6619.

person's reduced lifespan (which is the sort of issue courts deal with routinely), but instead the more tractable question of what is the value of reducing environmental risk.

One way to do this is observe what premium individuals must be paid to accept employment that entails greater risks of fatal accidents. Suppose, for example, the estimated wage premium is $500/yr. to compensate for an increased annual job-related risk of one death in one thousand. Then, if the risk of death to 1,000 people is reduced by .001, one life is saved on the average, and since each of 1,000 people is willing to accept $500 to take this risk, one statistical life is valued at $500,000. This amount is not a measure of compensation appropriate for a particular death, since no one knows which one of the 1,000 people will die from the hazard. In 1980 dollars, Mathtech's review of the risk literature indicates that a one unit reduction in annual mortality risk would have a statistical value of between $360,000 and $2,800,000 with a point estimate of $1,580,000.

Morbidity valuation accounts for three factors: the loss in work time due to illness; the reduction in activity levels on nonwork days; and direct medical expenditures. The first is valued using the average daily wage, while the second, somewhat arbitrarily, is valued at one-half the average wage. The specific wage rates vary geographically by county.

Health effects are divided into seven subcategories: subcategories (1) and (2) cover noncancer mortality effects due to short- and long-term exposure; subcategories (3) and (4) cover noncancer acute morbidity effects due to short- and long-term exposure; subcategories (5) and (6) cover noncancer chronic morbidity effects due to short- and long-term exposure; and subcategory (7) is for cancer mortality and assoicated morbidity. Research in some of these areas is very scanty, especially with respect to particulate effects, let alone work that specifically addresses diesel particulate effects. In fact, with the exception of the cancer area, the studies are based on measures of total suspended particles (TSP) rather then diesel particles. One might suspect that the fine diesel particles are potentially more damaging, given inhalation deeper into the lungs, but in the absence of direct evidence, the Mathtech study conservatively assumes TSP and DP exposures result in equivalent health effects.

The Mazumdar, Schimmel, and Higgins study [6] is selected (for aggregation Alternative C) as the best representative of short-term noncancer mortality effects. The long-term exposure mortality studies (e.g. Lave and Seskin [7]) are judged as too speculative to be included in the estimate used here. The Mazumdar et al. work is a longitudinal study of daily mortality during 14 London winters. Using both exposure to British Smoke and SO_2, short-term exposure dose-mortality functions are estimated using excess daily winter mortality as the dependent variable. Both lagged and nonlinear models are tested. The main limitation to the work is that both pollutants are not present in one regression estimate, so that omitted variable bias is possible. While this and other difficulties are apparent in Mazumdar et al, their results are credible, and there are no alternative estimates of short-term mortality effects.

In the short-term chronic noncancer mortality area, the Ferris studies with various coauthors [8] constitute the best choice. These examine chronic respiratory disease at one location over three time periods during which TSP declined. From the three studies, it can be concluded that respiratory health effects are observable when TSP is in the range of 180 mg/m^3 down to 130 mg/m^3, but that either no beneficial effect occurs as concentrations are further lowered to 80 ug/m^3 or the effect is obscured, perhaps by changes in SO_2 concentrations. The Ferris studies are valuable because disease incidence is classfied by age and sex, and cigarette smoking is taken into account. Though Ferris et al. did not derive concentration-response functions, health effects can be tied to appropriate aerometry data.

The Ostro [9] study is selected for the long-term acute morbidity category. It uses the 1976 National Center for Health Statistics Health Interview Survey to estimate the relationship between long-term exposure to TSP and sulfates and acute illness, measured in work-loss and reduced-activity days. The data covers both worker and nonworker respondents in 84 SMSAs. The author attempts to statistically control for a broad array of sociodemographic differences in respondents in addition to pollution and weather related variables in his concentration-response functions. Both linear and logit models are tested. The Ostro study covers a broad range of respiratory effects and is very thorough in its statistical analysis, providing a sound basis for the concentration-response functions in the acute morbidity category.

The cancer mortality and associated morbidity estimates are based on the results from several studies, reviewed in the OMS Diesel Particulate Study [10], and a study by Harris [11]. These studies examine the incidence of respiratory cancer due to occupational exposure to coke oven emissions and roofing tar. These results are coupled to laboratory studies on the potency of diesel particles relative to these substances to predict the incidence of respiratory cancer from diesel particles. It is important to emphasize that the underlying studies do not relate occupational cancer to diesel particles, and that use of surrogates introduces considerable uncertainty. There is simply no alternative in the absence of a direct and credible epidemiological study.

The valuation of cancer risks parallels the procedures used for noncancer health risks. While this ensures consistency and comparability, the results can differ substantially relative to those constructed on a steady-state basis. Cancers that are predicted to occur after the year 2000 are included in the Mathtech analysis. However, three independent factors reduce the significance and value associated with the potential loss of life. First, some portion of the people exposed to carcinogenic diesel substances die from other causes before the onset of respiratory cancer symptoms. Second, the reduced exposure to potential diesel carcinogins is assumed to occur during the fourteen year analysis period, which covers only part of the usual lifetime risk. Finally, the long disease latency period means actual incidence is 20 to 40 years beyond the initial year of analysis, and everything is discounted back to that year. At a 10% rate of discount, even large numbers are substantially reduced over this long a period. Since the cancer benefit category turns out to be quite small, sensitivity analysis to these procedures was undertaken. The results of these are reported in the next section.

In sum, while the quality of information from the studies included in aggregation Alternative C is mixed, there will be some natural offsetting of errors. In light of the fact that there are gaps in the coverage (ensuring the probability of double-counting is minimal), the overall health benefit estimate is probably on the conservative side.

3. Estimation of Welfare Benefits

Recent economic research suggests that the general welfare category of benefits (i.e. nonhealth benefits) may be an important part of the total benefits derived from air quality improvement programs (See Freeman [12]). Diesel particles degrade visibility and contribute to soiling and other material damages. Though these effects are sometimes accorded secondary importance, the dollar a consumer is willing-to-spend to mitigate these impacts is no different than a dollar he might be willing-to-pay to reduce risks to health.

Reduction in visual range is associated with the concentration of fine particles, of which diesel particles are a part. Thus, control of diesel particulate emissions may generate benefits via improved visibility. Consumers experience the benefit in conjunction with outdoor activities or simply because they value the preservation of scenic views. Economic studies of visibility rely on contingent valuation techniques which make use of specially designed surveys.

The valuation of visibility improvement is based on the results of two studies: Tolley and Randall [13] and Brookshire, d'Arge, Schulze, and Thayer [14]. The Brookshire *et al*. study, which was conducted in the Los Angeles area, is used to develop benefit estimates for urban counties in the western United States. The Tolley and Randall study, conducted in Chicago, is used to value urban counties in the eastern United States. These studies do not project changes in visual range -- Mathtech does this utilizing Koschmieder's Law.

While over the past decade economists have developed and tested many types of contingent valuation instruments to value aesthetic changes, the technique has not yet fully gained professional acceptance. Different attempts to value similar goods have yielded substantially different values. Two points are worth emphasizing. One, when available, the use of market data will provide a more accurate valuation. Two, while contingent methods are less accurate, there often are no alternatives for valuing aesthetic changes with public good characteristics, and a less accurate valuation is preferable to leaving the resource unvalued (which is sometimes incorrectly perceived as equivalent to a valuation of zero).

Briefly, the contingent valuation approach relies on a highly structured questionnnaire that places respondents in a hypothetical market situation. The questions are designed to elicit responses that either directly or indirectly reveal their preferences about changes in environmental quality--in this case in visibility as measured by visual range. This information is conveyed through the use of a set of photographs that depict a familiar scene under different visibility conditions. In one variant of the procedure, a specific method of paying for improved environmental quality is suggested (e.g. an increase in utility bills or taxes). This is designed to convince respondents that their dollar "votes" involve real resources and to discourage "free-rider" responses. Bids for improved environmental quality are solicited directly, though sometimes an iterative procedure is employed. In a second variant of the procedure, respondents are asked to rank outcomes -- consisting of a hypothetical payment and a corresponding level of environmental quality -- from most preferred to least preferred.

Two factors of this methodology have led to concerns about the results. First, the public good nature of environmental quality may lead respondents to purposefully misstate their true preferences. Repeated testing for the occurrence of strategic response has not found this to be a serious concern. Second, there are many inherent potential biases in the design and administration of surveys. The wording of questions can influence responses, sometimes significantly. These built in survey biases continue to be a concern, and undoubtedly are the ultimate limit on the accuracy of the contingent technique.

The Brookshire et al. study used data from six paired areas in the southern California region. Good, fair, and poor visibility conditions (2, 12, or 28 miles of visual range) were used in the choice of the paired census tracts; no pair had identical visibility conditions. Health effects information was distributed to some of the respondents. Using different question formats, Brookshire et al. were able to identify the non-visibility component of the total bid for visibility improvement. On average, the aesthetic component accounted for about 35 percent of the total bid. An analysis of the area-by-area bids indicates that the pure visibility value is approximately $6.35 (1980 dollars) per household per year for each mile improvement in visual range.

Using six separate contingent value question formats, Tolley and Randall valued changes in visual range over three distances in the city of Chicago: 9 to 4 miles, 9 to 18 miles, and 9 to 30 miles. Based on the latter two visibility scenarios, their analysis indicates that the value of a one mile change in visibility averages $18.50 (1981 dollars) annually per household. This bid may include non-visibility components. If the Brookshire et al. 35 percent factor is applied, the mean bid would be $6.60, which is remarkably similar to the Brookshire result in the West.

Soiling damages are estimated using a study by Watson and Jaksch [15]. It covers the household, but not the commercial or industrial sectors, where there may be material damages associated with diesel particle deposition. Watson and Jaksch utilize a simple supply-demand framework, where the supply of cleanliness shifts downward (reflecting a decrease in the cost of obtaining a given level of cleanliness) as emissions are reduced. This generates a gain in consumer surplus, which constitutes their estimate of soiling benefits.

There are a number of important assumptions embedded in their calculations. First, using the data from the Booz, Allen, and Hamilton [16] survey of cleaning expenditures, frequencies, and time durations for multiple household cleaning activities to calibrate the demand curve of their model, Watson and Jaksch reach the conclusion that actual cleaning expenditures do not change as pollution changes. That is, they assume a unit elastic demand curve for cleanliness. If, as seems at least as equally plausible, the demand for cleanliness is inelastic, the surplus estimates would be lower. Likewise, the functional form assumptions for the supply curve and the way it shifts could influence the benefits estimates, but the direction of bias cannot be determined *a priori*. Second, the underlying soiling survey data used TSP units. It has been asserted, by Wallin [17] and Sawyer [18], that diesel particles, because they are stickier, more oily, and darker, have 4 to 5 times the soiling potential of TSP. Mathtech treats this claim cautiously. It is quite unlikely that people spend four to five times as much for cleanup as CARB recently assumed in a soiling estimate for California. Mathtech does however, double their upper-bound soiling estimate to account for this effect. In sum, there are offsetting biases that influence the Watson-Jasch estimate of soiling. Since a different study provided similar, though somewhat higher values, the Watson-Jaskch benefit estimate is the conservative choice.

4. Summary of Results and Sensitivity Analysis

The basic results are summarized in three tables. Table 8-2 shows the lower-bound, point, and upper-bound benefit estimates disaggregated by category for the .25 g/BHP-hr. standard. Table 8-4 illustrates the geographic distribution of these benefits. Table 8-5 provides a category-by-category benefit breakdown for two heavy-duty truck standards: .25 g/BHP-hr. and .10 g/BHP-hr.

Table 8-2 is designed to provide a sense of the uncertainty associated with the point benefit estimates. This uncertainty arises from numerous sources. Predicting the magnitude of air quality improvements involves use of CO as a proxy for DP and projections of the size and composition of the vehicle fleet until the year 2000. In addition to the uncertainties associated with these factors, the potential air quality improvement in counties adjacent to those included in the analysis is not counted. The evidence from the health and welfare studies that form the basis for valuation is at times contradictory. Even within studies, considerable variation is often apparent as a result of using different functional forms for concentration-response relationships. Sampling variation is sometimes large. Finally, the assumed equivalence of TSP and DP effects could be in error. The actual value assigned to response changes involves additional uncertainty. Overall, there is the potential to under or over count, given the fuzziness of boundaries between the health categories. Some benefit categories, for example diesel odor, are not included, and others are not fully valued, which could be the case for morbidity, where health cost and wage data are used in lieu of actual willingness-to-pay data.

Many of these uncertainties can be collapsed into two observed sources of error. There is variation in the results in different studies covering similar effects, and there is variation within a given study that results from sampling error and the use of sensitivity analysis to crucial assumptions. Mathtech provides information on both, by their use of different aggregation schemes and by provision of bounded estimates for the individual studies.

As indicated earlier, it would be a mistake to judge uncertainty on either of these alone, since the sources of uncertainty are associated with both. The upper- and lower-bound estimates attempt to account for both, but it is important to point out that without statistical information on the distribution of errors, no overall formal accounting of uncertainty is possible. Thus, the bounded estimates in Table 8-2 are subjective.* The following guidelines are employed. If the results from studies selected as credible in a given category are substantially different from the best estimate, the estimates from these other studies are incorporated into the lower- and upper-bound estimates. If, on the other hand, the studies are similar, the error bounds are then derived from the study used in Alternative C, taking account of statistical variation and variation in critical assumptions. Since these bounds are subjective, they cannot be interpreted as confidence intervals. They only indicate the full range of uncertainty that is present.

Table 8-3 summarizes the sources for the estimates in Table 8-2. In the noncancer mortality area, the lower-bound estimate is based on Mazumdar et al. utilizing assumptions on functional form, the value of risk, and confidence intervals for estimated parameters that give low estimates. The upper-bound estimate is based on the Lave and Seskin [7] study. It is used because it produced estimates quite a bit higher, though in general less reliable, than those from Mazumdar et al. Since the results of studies in the noncancer acute morbidity area differ substantially, studies other than Ostro are used for the upper- and lower-bounds. The lower-bound estimate is based on a study by Samet, Spiezer, Bishop, Spengler, and Ferris [19] and the upper-bound by Crocker et al. [20]. There is likewise considerable range in the benefit estimates derived from studies in the noncancer chronic morbidity area. With a point estimate of $21 million, the lower-bound estimate cannot realistically be distinguished from zero. The upper-bound estimate is based on the chronic effects research of Crocker et al. In the cancer area, the lower-bound estimate is zero, based on the studies EPA reviewed [10], while the upper-bound estimate is based on Harris [11].

In the visibility welfare area, the underlying contingent market studies are very similar. However, standard errors of the estimated average bids are not reported. Thus, the upper-bound estimate is based on the SRI [21] study, which has the highest bid for a given change in visibility. The lower-bound estimate would be considerally larger than the $100 million shown in Table

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*Mathtech did not follow such a procedure. The upper- and lower-bound estimates reported in Table 8-2 are based on extrapolation and reorganization of results reported in the Mathtech analysis.

Table 8-2

Benefits of Heavy-Diesel Particulate Standard of .25 g/BHP-hr.*

Benefit Cateogry	Lower-Bound	Point	Upper-Bound
Health			
Noncancer Mortality	6.	187.	1802.
Noncancer Acute Morbidity	351.	3035.	8418.
Noncancer Chronic Morbidity	0.	21.	2250.
Cancer Morbidity & Mortality	0.	1.	18.
Health Subtotal	357.	3244.	12,488.
Welfare			
Visibility	100.	1987.	3001.
Household Soiling	786.	1404.	5616.
Welfare Subtotal	886.	3391.	8617.
Total Benefits	1243.	6635.	21,105.

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* Present value over 1987-2000 interval in 1987 measured in millions of 1983 dollars. Annualized values for 14 year interval at 10% discount rate can be obtained by dividing entries by 7.367.

Table 8-3

Source Summary of Lower-Bound
Upper-Bound and Point Estimates

Benefit Cateogry	Lower-Bound	Point	Upper-Bound
Health			
Noncancer Mortality	Mazumdar	Mazumdar	Lave & Seskin
Noncancer Acute Morbidity	Samet	Ostro	Crocker
Noncancer Chronic Morbidity	Ferris	Ferris	Crocker
Cancer Morbidity and Mortality	EPA*	EPA*	Harris
Welfare			
Visibility	Tolley & Randall, Brookshire _et_ _al_.	Tollery & Randall Brookshire _et_ _al_.	SRI
Household Soiling	Watson & Jaksch	Watson & Jaksch	Watson & Jaksch

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*Encompasses several studies reviewed in EPA Diesel Particulate Study [10]

8-2, if it were based on the low estimates from the contingent market literature. However, as indicated in chapter 5 of this RIA, the increases in visibility attributed to control of diesel particles range from 1.2 to 7.0 percent (See Table 5-4). Only one city in the Mathtech's forty-one county coverage has a visibility increase exceeding one mile. Improvements much less than one mile are probably not perceptible, and since the contingent market evidence is predicated on questions designed on 5 or 10 mile changes in visual range, whether or not consumers value a change that they can barely perceive is conjectural.* The $100 million estimate is conservatively derived assuming only 1 in 40 counties have enough improvement in visibility to be noticeable and valued. As with the visibility studies, the household soiling studies are similar. Thus, the lower- and upper-bound estimates are based on the Watson and Jaksch analysis, by varying a shift parameter in the supply function.

As apparent from Table 8-2, the health benefits are roughly equal to the welfare benefits. Noncancer acute morbidity, visibility, and soiling account for almost all the total benefits. Noncancer mortality and noncancer chronic morbidity are relatively unimportant, though there is some potential for significant effects in these areas as indicated by higher upper-bound estimates. The best information available points to a rather small cancer benefit associated with reduced diesel emissions. It is important to note that diesel odor is an important omitted welfare category.

Generally, the uncertainty is greatest in the health relative to the welfare area. The uncertainty is decidedly nonsymmetrical, with greater uncertainty on the lower end. The net result of these two factors is that the lower-bound total benefit estimate is influenced most by the greater certainty of welfare effects, particularly soiling; in contrast the upper-bound total benefit estimate is influenced more strongly by the health categories.

Table 8-4 shows the regional distribution of benefits. The benefit-cost criterion establishes whether or not a regulation is efficient. This means that those that benefit gain more than those who bear the costs. Distributional consequences, being separate from efficiency concerns, are usually judged on noneconomic grounds.

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*It should be pointed out that programs to reduce particles from other sources in conjunction with diesel vehicles could very well improve visibility substantially. The multiprogram improvement, of which diesel control is a part, would be highly valued.

Sometimes, when the groups bearing the costs are noticeably different from those deriving the benefits, perhaps separated geographically as in the case when pollutants are transported long distances, the question of property rights becomes the paramount policy concern. This does not seem to be the case with the diesel particulate emission issue. While some areas have larger diesel loadings than others, as reflected in the results of Table 8-4, the costs of control are diffused among the owners of heavy-duty trucks and the customers of transported goods and services.

Table 8-5 compares the benefits of a .25 g/BHP-hr. standard to a .10 g/BHP-hr. standard. The results are exactly what one would expect.

It is desirable, to the extent possible, to test the sensitivity of results to key assumptions. This has been undertaken in three areas: (1) with respect to the assumed diesel sales penetration rate; (2) with respect to the real discount rate; and (3) with respect to the use of discounting and accounting for prior causes of death in the cancer area.

Forecasting diesel sales as a fraction of total sales out to the year 2000 clearly involves a significant amount of guesswork. Thus, additional analysis assumed that heavy-duty trucks under 26,000 lbs. gross vehicle weight have a market penetration rate 25 percent higher than in the basic analysis. The heavier trucks, over 26,000 lbs. gross vehicle weight are left unchanged, since most trucks of this weight are already diesel. The result is that total benefits increase by less than 5 percent. Thus, errors in predicting heavy-duty diesel penetration rates are not very important.

The second sensitivity check was with respect to the use of a real rate of discount of 10 percent. This choice of rates is in line with OMB guidelines for the preparation of RIAs. Much debate surrounds the choice of the correct rate, and no consensus has formed. Most economists believe, however, that 10 percent is too high. To test sensitivity to the use of the 10 percent real rate, the benefits were re-calculated using a discount rate of 5 percent. With this change, benefits increased approximately 93%. This will not significantly influence net benefits (total benefits minus total costs), however, since total costs will also approximately double, given the relatively smooth stream of equipment and maintenance costs. Details of the cost calculation are discussed in the following section.

Finally, recall that the calculations for cancer benefits, though comparable to other health areas, intrinsically tend to give low values. Two sensitivity checks were run. First, given the latency period, most of the lives lost to respiratory cancer

Table 8-4

Geographic Distribution of .25 g/BHP-hr. Heavy-Duty Diesel Particulate Standard Benefits*

EPA Region		Total Benefits
I	New England	184.
II	New York - New Jersey	612.
III	Middle Atlantic	544.
IV	South Atlantic	812.
V	East N. Central	1258.
VI	South Central	661.
VII	Midwest	173.
VIII	Mountain	242.
IX	South Pacific	1890.
X	North Pacific	260.
U.S.	Total **	6635.

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*Present value over 1987-2000 interval in 1987 measured in millions of 1983 dollars.

**U.S. total has been computed prior to rounding so that amount indicated differs slightly from the actual sum of regional benefits.

Table 8-5

Benefits of Heavy-Duty Diesel Particulate Standards*

Benefit Cateogry	Standard .25 g/BHP-hr.	 .10 g/BHP-hr.
Health		
Noncancer Mortality	187.	262.
Noncancer Acute Morbidity	3035.	4272.
Noncancer Chronic Morbidity	21.	30.
Cancer Morbidity and Mortality	1.	1.
Health Subtotal	3244.	4565.
Welfare		
Visibility	1987.	2909.
Household Soiling	1404.	1981.
Welfare Subtotal	3391.	4890.
Total Benefits	6635.	9455.

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*Present value over 1987-2000 interval in 1987 measured in millions of 1983 dollars.

occur 20 to 30 years after 1987. The value of reducing the risk of death this far out in time is substantially reduced by the 10 percent rate of discount. To find out how much this matters, the discounting is removed. Thus, people are assumed to value a reduction in risking immediate death the same as death much later in their lifetime. The point estimate increased by a factor of 6, and the upper-bound estimate increased by a factor 4. This is somewhat perplexing. Since the time period covered over 50 years, it was believed a priori that discounting would have a larger impact. Thus, a second sensitivity check was run. Some individuals exposed to diesel particles in the period 1987-2000 will die of other causes prior to the manifestation of cancer. When this assumption is removed, along with the use of a 0 percent discount rate, the point cancer benefit estimate approximately increases by a factor of 30, and the upper-bound estimate by a factor of 14. Of course, one might question whether one should attribute risk to cancer, when the actual cause of death is expected to be unrelated to cancer. In any case, while under different assumptions cancer benefits would be larger, they would still be small relative to noncancer health effects.

B. Particulate Cost Analysis for HDDVs

1. System and Operating Trap-Oxidizer Costs for HDDVs

In this subsection, the component and operating costs for equipping a HDDV with a trap-oxidizer will be estimated. The primary estimate is based on EPA analysis from the Diesel Particulate Study [10]. Since this estimate is in point form, other analysis, in particular from a study by Energy Resource Consultants (ERC) that was summarized in a recent SAE paper [21], is used to develop a range estimate. As was the situation in the benefit analysis, statistical control of estimated errors is not possible with the available data. Thus, no formal accounting of uncertainty is possible. Rather, to parallel the benefit analysis, lower-bound, point, and upper-bound estimates are provided. These are subjective and are only meant to provide a sense of the measurement uncertainty on the cost side. In the following section the component and operating cost estimates are used to calculate the total discounted control costs associated with the .25 g/BHP-hr. and .10 g/BHP-hr standards.

Table 8-6 summarizes the EPA and ERC cost analyses. Where comparisons are possible, the estimates differ by 30 to 80 percent. Some of the difference is explained by the nature of the approximations. Accurately estimating the fuel penalty is particularly tricky, since there is little operational data available. It should also be noted that EPA and ERC use somewhat different definitions of truck classes.* By and large, however, the difference in estimates is due to different assumptions concerning dealer margins on pollution control equipment, and on different cost estimates for equipment components.

Both analyses follow the costing procedures developed by Lindgren [22] to obtain the "Retail Price Equivalent" (RPE) which is used as the equipment cost estimate shown in Table 8-6. The RPE is found by estimating the cost of the components in a trap-oxidizer system to the manufacturer, and then adding markups to account for the cost of assembly and the manufacturer's and dealer's profit and overhead. Component costs are based on data for light-duty trap-oxidizers, data from manufacturers, and engineering judgment. A simplified version of the formula is:

RPE = [Variable and Fixed Manufacturing Costs] x [1 + Corporate Level Overhead + Corporate Profit + Dealer Overhead and Profit]

EPA and ERC follow the Lindgren guidelines faithfully at the manufacturer level, but differ substantially in estimates of the markups in the second bracket. ERC uses the Lindgren estimates of .2, .2, .4 for corporate overhead, corporate profit, and dealer overhead and profit, respectively. EPA substitutes lower estimates at the dealer level, which results in the overall bracketed factor being equal to 1.2 in lieu of 1.8.

EPA's reasoning for adopting lower markup factors is summarized in a 1980 report [23]. EPA found for the 1976-1978 period that corporate overhead as a percentage of sales was about 10 percent, and corporate profit (for GM) 14 percent. These are smaller than the 20 percent estimates for both categories used by Lindgren. Using the argument that the incremental cost of sales at the dealer level is the appropriate markup (that is, unless the control device itself adds to overhead, fixed costs should not be attributed to the cost), EPA found that dealer profit as a percent of sales before taxes amounted to 3 percent in 1977, and used this in lieu of Lindgren's 40 percent estimate.

The perspective reflected in the Lindgren analysis and ERC's estimates is different. EPA, in effect, assumes that any cost producing change, whether for safety purposes, to improve performance, or to reduce emissions, does not add much incrementally to cost at the dealer level. Overhead in this view is independent of vehicle sticker prices and gross sales. In contrast, the Lindgren view is that all costs are variable, so that cost producing change should be included in dealer margins. While EPA's procedure probably more closely approximates actual market conditions, this area has not been carefully analyzed, in particular as it applies to the retail market for trucks. Thus, a comparison of the two estimates provides a gauge of a portion of the cost uncertainly.

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*EPA divides the classes into: 8500-19,000 lbs., 19,000-26,000, and 26,000 and up; ERC into 8,500-14,000, 14,000-40,000 and 40,000 and up.

There are differences in the control cost estimates as well as in the markup factors. The use of stainless steel piping reduces maintenance on the exhaust system. EPA accounts for this, the ERC estimates do not. The result is that the EPA cost estimates for maintenance indicate net savings (i.e., they are negative). However, even without the maintenance savings the ERC maintenance estimates are larger than the EPA figures. Thus, with the exception of the fuel penalty estimates which are quite similar, the ERC estimates for equipment and maintenance are larger than EPA estimates. Using EPA markup factors, ERC's estimated equipment costs are 22, 2, and 44 percent higher than for comparable EPA equipment for the three truck weight categories respectively.

In sum, the ERC estimates are uniformly higher than EPA's estimates. Since EPA addresses the markup issue more realistically and is somewhat more detailed, it serves as the best, or point estimate. Even so, it is clear that some uncertainty exists on the appropriate markup and on equipment costs, that is reflected in differences between the EPA and ERC estimates. Since the ERC estimates are the larger of the pair, they are utilized to compute an upper-bound estimate. The lower-bound estimate is based on the EPA calculations: no credible evidence exists that the costs could be substantially lower. In the following section these vehicle cost estimates will be used to derive lower-bound, point, and upper-bound total cost estimates for the 1987-2000 period.

2. Total Discounted Consumer Costs

The basic calculation of discounted total cost is straightforward. For each model year, starting in 1988 and running through the year 2000, the equipment and operating costs detailed in the previous section are allocated over the typical truck's lifetime. This can be done in one of two ways. The vehicle costs can be annualized so that the costs are spread uniformly by year over the vehicle's lifetime, or they can be allocated in the year in which they occur. Normally, the latter procedure is most appropriate, since it reflects the timing of actual resource costs of achieving emissions reductions. In this application, however, the annualized allocation of a model year's cost makes more sense. The reason for this is best understood by examining the benefits and costs of control for a vehicle manufactured toward the end of the analysis period, say in 1999. With control devices installed, this car will continue to emit fewer particles in 1999 and 2000 and well

Table 8-6

Estimated Lifetime Vehicle Costs for Trap-Oxidizer Systems in HDDVs (1983 dollars)

		Discounted Costs		
Class/Technology/Source	Equipment	Maintenance*	Fuel Penalty	Total
I. Light-Heavy Trucks				
Burner Monolith — EPA	$363.	($17.)	$126.	$472.
— ERC	624.	47.	116.	787.
Catalytic — EPA	754.	—	—	—
— ERC	740.	13.	87.	840.
II. Medium-Heavy Trucks				
Burner Monolith — EPA	$556.	($17.)	$386.	$925.
— ERC	800.	60.	369.	1229.
Catalytic — EPA	1207.	—	—	—
-- ERC	1140.	17.	276.	1433.
III. Line-Haul Trucks				
Burner Monolith — EPA	$652.	($53.)	$917.	$1516.
-- ERC	1320.	295.	1107.	2722.
Catalytic — EPA	1444.	—	—	—
-- ERC	2140.	1052.**	738.	3930.

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*Parentheses indicate negative maintenance expense. See text for explanation.

**Includes discounted cost of replacing catalyst at 250,000 miles.

beyond. The benefits of control are not counted after 2000. Thus, if the costs of control were allocated as they actually accrue, substantial equipment costs are recorded in the year of purchase, with only operating costs, thereafter. This front-loading will mean will that most of the costs are counted, in contrast to only two years of the benefits. If, however, the costs are annualized, two years of costs will be compared with two years of benefits.

Using the latter procedure,* each of the model year's costs are recorded on a spreadsheet, each entry computed by multiplying per vehicle costs by projected sales. The costs are summed by year, then discounted, and finally summed over the years in the 1987-2000 interval to give the final result. The worksheet of the computations based on ERC estimates for the burner-monolith trap-oxidizer technology is shown in Table 8-7 as an example of this procedure.

As was the case with the benefit estimates, emissions control costs are not estimated with certainty. Total cost estimates in range form are derived from Table 8-7 and a similar spreadsheet analysis of EPA cost estimates. The lower-bound and point estimates are based on EPA vehicle cost estimates, while the upper-bound of the range is based on ERC cost estimates. Total cost estimates for the .25 g/BHP-hr. and .10 g/BHP-hr. standards are shown in Table 8-8. Table 8-7 was derived assuming 100% trap usage, which corresponds to the .10 g/BHP-hr. standard. Total control costs for the .25 g/BHP-hr. are computed by applying the 70% trap usage factor calculated in the Diesel Particulate Study [10] to the results obtained from the spreadsheet analysis. The 70% trap usage factor assumes that emissions averaging is permissible.

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*As indicated, this is not the conceptually correct procedure. If the information to implement it were available (it is not), the following procedure would be preferable (though the overall result in all probability would remain the same in this application). On the cost side, control costs should be allocated as they occur. On the benefit side, the benefits accruing from emissions reductions beyond 2000 from vehicles manufactured prior to 2000 should be calculated, discounted, and added to discounted benefits in the 1987-2000 interval. In this way all the benefits and costs associated with vehicles manufactured in the 1987-2000 interval are counted at the time they actually occur.

Table 8-7

Spreadsheet Total Cost Analysis for HDDV Particulate Control

Calendar Year

Model Year	87	88	89	90	91	92	93	94	95	96	97	98	99	2000
87														
88		92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	76.8	76.8	76.8	14.8	—
89			97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	80.0	80.0	80.0	15.9
90				101.9	101.9	101.9	101.9	101.9	101.9	101.9	101.9	83.6	83.6	83.6
91					106.4	106.4	016.4	106.4	106.4	106.4	106.4	106.4	86.8	86.8
92						111.5	111.5	111.5	111.5	111.5	111.5	111.5	111.5	90.5
93							116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0
94								121.1	121.1	121.1	121.1	121.1	121.1	121.1
95									125.8	125.8	125.8	125.8	125.8	125.8
96										130.9	130.9	130.9	130.9	130.9
97											135.4	135.4	135.4	135.4
98												140.5	140.5	140.5
99													145.0	145.0
2000														150.1
Column Total	0	92.5	189.5	291.4	397.8	509.3	625.3	746.4	872.2	987.4	1105.8	1228.0	1291.4	1341.6
Discounted Total	0	84.1	156.6	218.9	271.7	316.1	352.9	383.0	406.8	418.7	426.3	430.4	411.5	388.6

Notes (following page

Notes for Table 8-7

1. Entries in table are in undiscounted millions of 1983 dollars. It is assumed that all vehicles manufactured have a burner-monolith trap installed. Policies that require fewer traps can easily be evaluated on a proportional basis.

2. Per vehicle costs are based on ERC estimates in Table 7-6, which have been annualized as shown:

	Vehicle Class		
	light-heavy	medium-heavy	heavy-heavy
Average lifetime	8 year	12 year	11 year
Annualized cost per vehicle	147.52	180.37	419.09

3. The ERC estimates provide the upper-bound total cost estimate. A similar spreadsheet was constructed for the EPA estimates, which provided the basis for the lower-bound and point total cost estimates. (see text.)

Table 8-8

Particulate Control Costs for HDDVs*

Standard	Lower-bound	Point	Upper-bound
.25 g/BHP-hr.**	1788.	1788.	2986.
.10 g/BHP-hr	2554.	2554.	4266.

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*Present value over 1987-2000 interval in 1987 measured in millions of 1983 dollars. Annualized values for 14 year interval at 10% discount rate can be obtained by dividing entries by 7.367.

**Assumes 70% trap usage factor under emissions averaging. Without averaging, trap usage under the .25 g/BHP-hr. standard would be near 100%.

C. Benefit-Cost Comparisons for Particulate HDDV Options

There are six HDDV particulate control options under consideration. (Refer to Table 7-1 for key information pertaining to these options.) In all cases, significant control is proposed in 1990, with an interim standard of .6 g/BHP-hr. in effect in 1987. Baseline emissions are assumed to be .7 g/BHP-hr. The 1990 standards range from .4 g/BHP-hr. down to .1 g/BHP-hr. Averaging of emissions is permitted in three options, and line-haul trucks are exempt from the 1990 standard in two variants. See Table 8-9 for a list of options (option numbers correspond to those in Table 7-1). The benefit and cost estimates of achieving each option are summarized in this table along with a tabulation of net benefits (benefit - cost). The information in Table 8-9 is based on analysis from earlier sections of this chapter, though the results are presented in annualized rather than present value form. The annualized dollar basis is necessitated by the need to have benefit and cost estimates independent of the policy initiation date, which differs between the options in this section and those examined in previous sections.

Options 4A and 5, .25 and .1 g/BHP-hr., respectively, with averaging permitted on the former, are identical to those considered previously, except for implementation dates. Thus, the cost and benefit estimates are derived directly from Tables 8-2, 8-5, and 8-8 for these options. The point estimate for net benefits is computed as the difference between point estimates for benefits and costs. The lower-bound net benefit estimate is calculated by substracting the upper-bound cost from the lower-bound benefit estimate. Similarly, the upper-bound net benefit estimate is calculated by subtracting the lower-bound cost from the upper-bound benefit estimate.

Option 4 is similar to option 4A, except emissions averaging is not permitted on the former. The benefit of option 4 is equal to that of option 4A, given the same level of reduced emissions. The cost of option 4 is higher -- essentially equivalent to the cost required to meet the .1 g/BHP-hr. standard -- since trap usage is 100%.

Option 3 is less stringent than options 4 or 5. The benefit estimate for option 3 is extrapolated linearly on the basis of relative emissions reductions using the .25 and .1 g/BHP-hr. estimates from the previous section. (See Table 7-1 for urban emissions reductions for relevant options). The .4 g/BHP-hr. standard can be met without usage of traps for most vehicles. The cost estimate for option 3 is derived using EPA estimates of requisite engine modifications as a proportion of the costs of achieving option 4A.

Options 4B and 4C are the split standards. They are proposed because line-haul trucks operate between cities and only contribute marginally to urban loadings. Yet, the cost of particulate control on a vehicle basis is quite high for line-haul trucks which fall into the heavy-heavy class. (See note to Table 8-7 for cost comparison.) The cost of meeting options 4B and 4C are computed on the basis of relative cost reductions similar to the calculation required in option 3. The benefits are extrapolated on the basis of relative reduced emission loadings, again similar to the calculation required in option 3.

In most important respects, the benefits and costs reported in Table 8-9 are comparable. Each is based on similar air quality information. Each is valued in 1983 dollars, and reflects a common time horizon and common discount rate. This does not mean, however, that the accuracy of estimating benefits and costs is always high enough so that differences between benefits and costs are necessarily significant. The many caveats throughout this chapter should make it clear that this may not be the case. Thus, the results reported in Table 8-9 should be viewed in conjunction with the uncertainty analysis reflected in the lower-bound and upper-bound estimates.

With this perspective, several results come through rather clearly. First, the benefits outweigh the costs across all options, and for the most part by an amount that is large. That is, the difference between benefits and costs are typically larger than the magnitude of the costs. Thus, it seams reasonable to conclude that some degree of further control of diesel particulate HDDV emissions is efficient from a societal perspective. Second, obtaining a ranking of options on an efficiency basis involves far more uncertainty. The differences in the point estimates of net benefits are smaller than the apparent magnitude of estimation errors. Thus, while the best estimate of net benefits for option 4A indicates that it is better than options 3 and 4, for example, there is a real possibility option 3 or 4 may in fact be better. This is evident since the upper-bound net benefit estimates for options 3 and 4 are at least a factor of three higher than the point estimate of option 4A.

While the lower-bound estimates of net benefits are uniformly negative, we do not conclude that the "no control" possibility should be considered seriously. In the first place, the lower-bound net benefit estimates are based on the difference between the lowest conceivable benefit and highest conceivable cost, and thus do not represent a very probable outcome. However, they provide useful information, especially to a risk-adverse decision maker. Given no significant basis for choosing between options 4 and 4B, for example, a risk-adverse individual would probably prefer option 4B, with a much smaller lower-bound negative net benefit. The same could be said for option 3.

In sum, option 4A is the preferred choice on an economic efficiency basis. Option 5 has higher net benefits, but not significantly so, and it entails some risk of a policy error given the large negative lower-bound net benefit estimate. Options 3 and 4 do provide positive net benefits in all probability. However, option 4A would always be preferable to option 4, given they are identical except that option 4 is necessarily more costly given averaging is not permitted. In addition, option 4 has the disadvantage of a high lower-bound negative net benefit estimate. The first of the split options, 4A, is almost identical to option 3 while the more stringent split standard, 4B, has marginally higher net benefits.

Table 8-9

Benefit-Cost Summary of HDDV Particulate Control Options (annualized millions of 1983 dollars)

	Benefit			Cost			Net Benefits		
	lower-bound	point	upper-bound	lower bound	point	upper-bound	lower bound	point	upper-bound
- .6 - .4	119.	632.	2010.	113.	113.	189.	-70.	519.	1897.
- .6 - .25	169.	901.	2865.	347.	347.	579.	-410.	554.	2518.
- .6 - .25(A)	169.	901.	2865.	243.	243.	405.	-236.	658.	2622.
- .6 - .25(A) - .6 line haul HDDVs	117.	622.	1977.	114.	114.	191.	-74.	508.	1863.
- .6 - .25(A) - .4 line haul HDDVs	148.	790.	2513.	177.	177.	295.	-147.	613.	2336.
- .6 - .1	240.	1283.	4082.	347.	347.	579.	-339.	936.	3735.

Baseline is assumed to be .7 g/BHP-hr.; (A) denotes emissions averaging permitted. See text for explanation of ntries in table, in particular for options not examined in previous sections of this chapter.

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